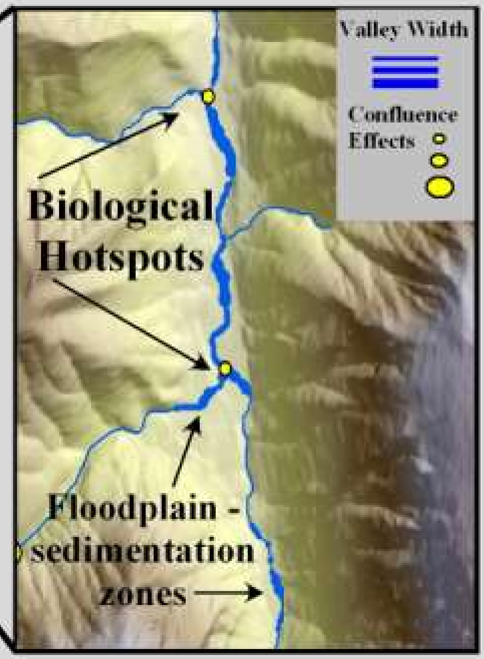
Terrain Resource Inventory and Analysis Database
(*TRIAD*)

Terrain Analysis Tools for Scientists and Planners



Supporting:
- Forest Management
- Landscape Planning
- Fish Habitat Management
- Flood Mitigation
- Hydroelectric Projects
- Watershed Restoration
- Monitoring/Research
- Conservation Planning
- Fire/Fuels Management

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Earth Systems Institute (ESI) is a non profit research and education organization developing new science and technology in the watershed sciences. See www.earthsystems.net for additional information on terrain analysis and other related projects and publications.

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ABSTRACT

The watershed sciences, together with the federal, state, private industry, and conservation organizations that use them, are in need of a method of landscape analysis that comprehensively describes the relationships between terrestrial and aquatic attributes of river basins that can be applied rapidly over large areas at low cost. Guided by recent ecological concepts that highlight landscape controls on river habitats including the importance of physical heterogeneity, and capitalizing on newly available techniques for topographic analysis of digital data, Earth Systems Institute's Terrain Resource Inventory and Analysis Database (*TRIAD*) identifies a watershed's riverine ecological potential and its relationships to natural and land use disturbances. *TRIAD* contains four parameter domains: basin topography and erosion processes, channel network configuration and valley morphology, channel (and habitat) morphology and sensitivity, and climate-driven disturbance. *TRIAD* provides two types of information. First is a high resolution (that of available digital elevation data) spatially registered and largely automated mapping of features in a watershed that govern erosion, network, valley and channel morphologic types, and sources of riverine habitat heterogeneity. For example, watershed maps are produced that indicate locations of highest erosion potential, highest potential sediment interactions with channels, highest quality habitats, and highest physical heterogeneity. The second type of information is based on parameters describing basin lithology, inherent erosion potential, basin shape, hillslope topography and roughness, network structure, channel types, valley morphology, and disturbance regimes within a queryable database. This information provides the *unprecedented* ability to search, sort, rank, and classify a population of watersheds to delineate attributes such as intrinsic erosion potential (i.e., lowest to highest), highest proportion of quality fish habitats, and highest morphological diversity, etc. Both types of information can be used to stratify landscapes for varying intensity of resource management, identify ecologically significant terrain for conservation, and to prioritize watershed and in-stream restoration and monitoring activities. The scale of analysis ranges from valley segment (1,000 – 10,000 m) to individual fish-bearing watersheds (100 – 1,000 km^2), landscapes (1,000 – 10,000 km^2), and to states and regions (>50,000 km^2).

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1. INTRODUCTION

Federal and state agencies, private industries, and conservation organizations that acquire and manage large tracks of land face a growing set of tasks related to assessing interactions between physical watershed processes and aquatic resources, including 1) stratifying watersheds for varying intensities of resource management, including fuels management, 2) delineating prime areas for conservation strategies, 3) targeting restoration projects, 4) prioritizing watershed and in-stream monitoring and research programs, and 5) extrapolating the results of such programs to other watersheds (Table 1). Despite the wealth of Geographical Information System (GIS) tools and analysis methods that can support some of those tasks, there is no comprehensive set that focuses on relationships between watersheds and their river networks at landscape and larger scales.

Earth Systems Institute (ESI) is developing a technology that treats physical watershed terrain as a “resource” (with respect to creating riverine habitats) that can be inventoried and analyzed to create a database, referred to as the Terrain Inventory and Analysis Database (or *TRIAD*). *TRIAD* can support watershed scientists and planners in applications concerning resource management, restoration, conservation, and research. The approach is based on current scientific foundations in geomorphology and riverine ecology that is appropriate for characterizing environmentally relevant attributes of watersheds over large areas at low cost. Because many of the parameters are described using digital elevation data (10 m at present), they focus more on general information rather than on reach-scale site-specific details (Figure 1). For example, *TRIAD* parameters focus on general habitat attributes associated with segment-scale channel gradients, valley confinement, and tributary confluences, etc., rather than on individual pools, log jams, and substrate sizes, etc. Despite the larger scale of analysis that is absolutely necessary when analyzing landscape scale and larger areas, such information has many potential uses in natural resource management and conservation particularly in mountain drainage basins.

Table 1. Potential user groups and applications of *TRIAD* at the individual watershed and landscape scales.
User Groups:
(1) Resource Management pertains to timber harvest, urbanization, grazing, water control projects (including dams and irrigation), and mining activities, etc.
(2) Restoration includes modifying channel and floodplain morphology by placing sediment, large wood, and engineering channel changes. It may also include erosion mitigation strategies such as road abandonment, etc.
(3) Monitoring refers to in-stream efforts to measure changing habitat and water quality conditions over time for evaluating land use regulations and restoration projects.
(4) Conservation includes acquiring or managing tracks of land primarily for environmental concerns.
(5) Research applies to developing study plans and field studies, and extrapolating their results across diverse watersheds.

USER Groups	OBJECTIVE	SCALE: INDIVIDUAL WATERSHED	SCALE: POPULATIONS OF WATERSHEDS
Resource Management	Evaluate land sensitivity to resource management	Map the juxtaposition of high hazard areas with areas of high quality habitats, biological productivity, or habitat diversity. Create maps of erosion susceptibility for specific applications, including fuels management.	Sort and rank watersheds based on intrinsic erosion potential, specific forms of erosion (mass wasting), channel sediment exposure, or wood accumulations, etc.
Restoration	Prioritize in-stream restoration projects	Create maps that identify the zones of the best intrinsic habitats. Identify areas predicted to be preferentially stable to increase success of restoration, or identify zones where river instability would decrease chance of success.	Sort and rank watersheds according to proportions of high quality stream habitats or by proportions of channels of various habitat types. Overlay basin maps of habitat quality with land use patterns and history.
Monitoring	Identify appropriate areas for in-stream monitoring projects	Develop maps showing locations of certain channel types and risk to sediment exposure to help identify where channel changes (and potential water quality impacts) are likely to be detectable with monitoring. Identify areas predicted to have large natural variability in channel environments for avoidance.	Identify and rank watersheds by channel types, erosion risk, or high intrinsic natural variability (i.e., intense natural disturbance regimes) to search out best potential monitoring sites (i.e., watersheds). Overlap the ranking of basins with land use patterns.

USER Groups	OBJECTIVE	SCALE: INDIVIDUAL WATERSHED	SCALE: POPULATIONS OF WATERSHEDS
Conservation	Identify land for conservation purposes	Create maps of individual basins showing the locations of all major sources of habitat, unique habitats, floodplain habitats, or zones of high habitat heterogeneity.	Sort and rank watersheds, or portions thereof, based on potential for high quality habitats, biological productivity, and physical diversity.
Research	Planning research programs and extrapolating results across diverse watersheds	Develop maps of individual watersheds that describe the suite of landscape – riverscape interactions to aid in selection of appropriate study sites.	Create a landscape/riverscape classification system that identifies similarities and differences among various parameter values to identify potential research sites and for extrapolation of study results.

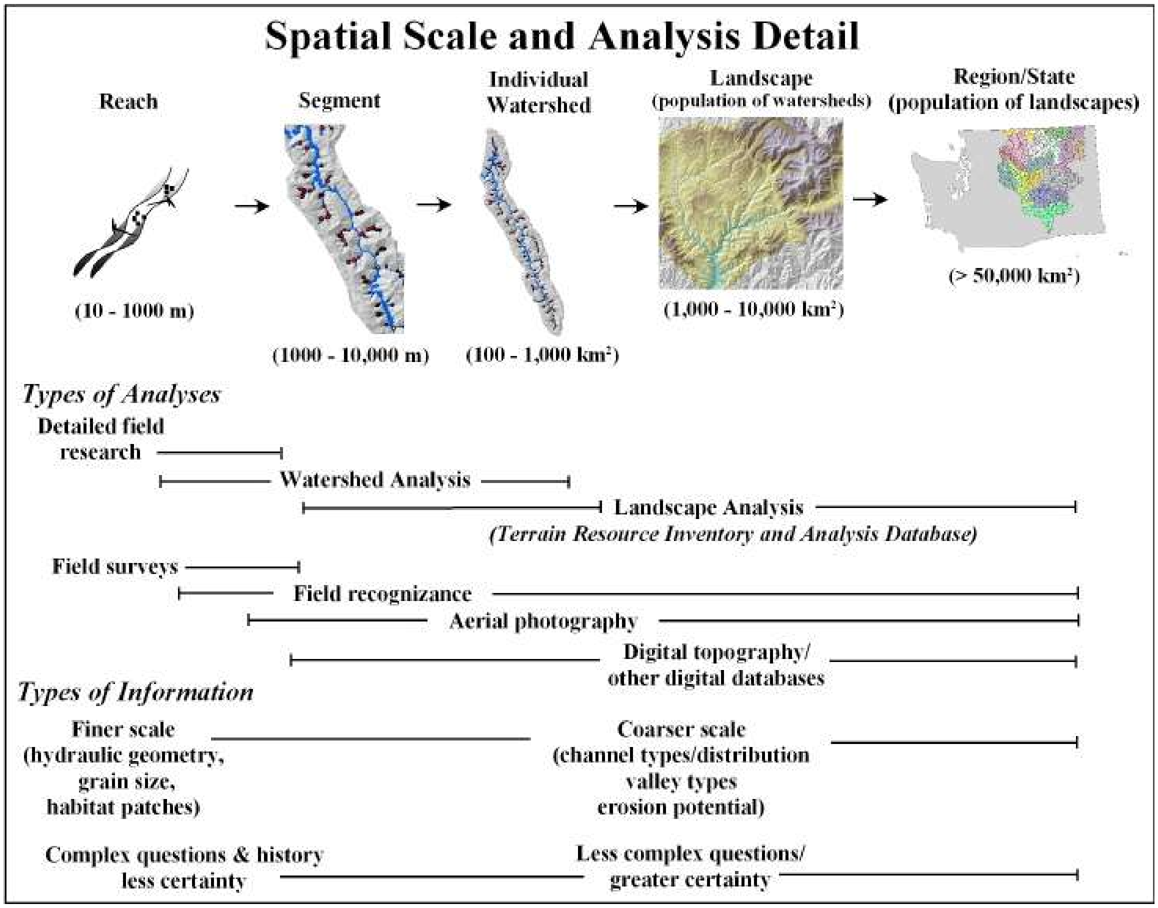

Figure 1. Analyses of watershed and river environments can occur at numerous scales. In general, detailed field research occurs at reach scales of 10 – 1000 m. Watershed analyses that collect more general information occur at the valley segment to small watershed scales (1000 m to < 1000 km^2). Analyses at landscape (1,000 – 10,000 km^2) to state and regional scales (> 50,000 km^2) are generally not available in the watershed sciences. The Terrain Resource Inventory and Analysis Database (*TRIAD*) described in this manual is designed to support landscape analyses for natural resource management at watershed to regional scales.

Part I of the *TRIAD* Users Manual contains this introduction and overview of the watershed database parameters. Part II describes web-based software designed to use and manipulate the watershed terrain database, including the unprecedented ability to search, sort, compare, rank, and classify watershed attributes. Part III of the users manual will contain illustrative applications including examples of how to combine groups of database parameters to understand the geomorphic and ecologic attributes of watersheds for scientists and planners. Also see www.earthsystems.net for additional information on the watershed terrain database.

1.1 Background

Terrain analysis defines a broad and interdisciplinary field of study that describes, maps, and classifies various aspects of the natural environment, including vegetation, watershed hydrology, topography, and erosion potential, etc. Although terrain analysis often involves GIS and computer analysis and visualization, field and aerial photo based techniques are also used to identify surficial materials, landforms, and geomorphic processes with applications for transportation systems, habitat mapping, forestry, and mining (WDNR 1995, Howes and Kenk 1997).

Terrain analysis could also be used to describe efforts aimed at mapping and classifying various ecological attributes of landscapes. For example, at the scale of continents, combinations of climate, vegetation, and physiography are used to classify landscape properties important in structuring terrestrial and aquatic ecosystems. The U. S. Environmental Protection Agency utilizes a set of "ecoregions" to establish biological and water quality standards and to set management goals for non-point-source pollution. Ecoregions encompass large areas: the entire western United States is comprised of 25 regions (Omernik 1995). The ecoregion approach lacks resolution at the scale of individual watersheds and cannot address landform-specific habitat forming processes, sources of habitat degradation, or disturbance and recovery processes (Boulton 1999, Berman 2002).

At a smaller scale but still regional in scope, the U. S. Forest Service defines "ecological subsections" based on landforms, parent materials, soils, vegetation, forest growth potential, and stream morphology (Nowacki et al. 2001). Although ecological subsections identify general relationships between hydrological properties of terrains and stream systems, they were not designed to provide detailed information on the relationship between individual watersheds and stream properties. Ecological classification by the U.S Forest Service (broadly termed ECOMAP) was also extended to aquatic ecosystems in a conceptual format that identified a nested hierarchical approach aimed at classifying watersheds, stream networks, valley segments, channel reaches, and channel units (Maxwell et al. 1995). However, its conceptual basis has not been translated into a comprehensive set of quantitative analysis tools.

Procedures to inventory various watershed attributes and assess sensitivity to resource use (such as timber harvest) contained within so-called "Watershed Analysis" methods (e.g., Washington State [WDNR 1997] and U.S. Forest Service [U.S.D.A 1995]) could also be considered a form of terrain analysis. Although some GIS is employed during watershed analyses, extensive use of aerial photography and field work generally requires large expenditures of time and money. For example, watershed analyses (applied at scales of 50 to 200 km^2) typically require a year or more per watershed with costs ranging between $200K and $1M. Similar expenditures occur during development of Habitat Conservation Plans. The practical limitation of applying relatively fine-scale environmental assessments over large areas (national forests, states, regions) is one of the problems of implementing the U. S. Forest Service's Northwest Plan (Thomas 2003).

Channel classification can be considered a form of terrain analysis, albeit limited primarily to channel environments rather than whole watersheds. Classification systems can be geographically independent (e.g., Rosgen 1995, Montgomery and Buffington 1997) or regionally specific (e.g., southeast Alaska [Paustian 1992]). Although valuable in their own right, existing stream classification systems do not account for many watershed-scale attributes that would tend to create unique riverine environments governed by basin topography, basin shape, network configuration, vegetation, and disturbance processes.

In summary, there presently does not exist a rapid inexpensive method of watershed-scale terrain analysis that can be used to stratify land for varying intensity of resource management, identify ecologically significant areas for conservation, and prioritize watershed and in-stream restoration and monitoring activities at the scale of landscapes, national forests, states, and regions.

1.2 Terrain Resource Inventory and Analysis Database for Watershed Scientists and Planners

TRIAD utilizes maps and numerical parameters to define relationships between the terrestrial and riverine components of landscapes (e.g., riverscapes), namely the types, abundance, and patchy distribution of riverine habitats and their sensitivity to change from natural disturbance and land uses. These include topographic and erosional controls on channel habitat formation, network, valley, and channel controls on habitat distribution and physical heterogeneity, and the role of disturbance on habitat formation. *TRIAD* uses techniques (numerical analysis of digital data, mapping from aerial photography, rapid field surveys) that can be applied at the scale of individual watersheds in a cost and time efficient manner over large areas.

The knowledge and tools described in this manual constitute a new technology that allows individuals with the proper training and experience to describe and interpret the multiple attributes and dimensions of landscapes and associated riverscapes at large scales, specifically major drainage basins, landscapes, national forests, states, and regions. Landscape analysis is relatively simple and straightforward because it is based on intuitive relationships between terrestrial aspects of landscapes and riverscapes, relationships that can be displayed in a highly visual format.

Often researchers and other disciplinary experts spend considerable amounts of time in a single geographic area studying watershed processes at very fine spatial and temporal scales. The tools contained in *TRIAD* will provide specialists and even generalists, including resource managers and planners, an opportunity to become proficient in interpreting diverse environmental attributes of watersheds and landscapes.

2. CONCEPTUAL AND METHODOLOGICAL BASIS OF *TRIAD*

2.1 Conceptual Developments in Riverine Ecology

Over the last 20 years three themes have emerged in riverine ecology that provide the conceptual basis for *TRIAD*: 1) habitat patchiness and heterogeneity, 2) habitat spatial hierarchies (multi-scaling), and 3) stochastic disturbance. The non uniform distribution of river habitats, or habitat patchiness, arises from downstream interruptions in channel and valley morphology associated with channel meanders, log jams, alternating canyons and floodplains, tributary confluences, and landslides, etc. (Bruns et al. 1984, Minshall 1985, Townsend 1989, Montgomery 1999, Rice et al. 2001, Ward et al. 2002). Such spatial variations in river habitats can occur over multiple, hierarchical scales, from the organization of stream-bed particles into bedforms to floodplain formation linked to valley segments (Frissel et al. 1986). Habitat patchiness occurs over a range of scales, including reach, valley segment, and watersheds (Figure 2).

An important source of heterogeneity is physical disturbances including fires, storms, floods, and erosion that dynamically create, alter, and maintain certain habitat features (e.g., Resh et al. 1988, Swanson et al. 1988, Reice 1994, Reeves et al. 1995, Poff et al. 1997). Concepts emphasizing disturbance are typically applied in the context of a particular location within a watershed (e.g., channel response to a landslide). From a watershed perspective, disturbance processes can also be examined in the context of a hierarchical and branched river network, through which sediment and wood fluxes from a series of stochastic events are organized into distinct temporal and spatial patterns, with ramifications for river morphology (Benda and Dunne 1997a,b, Gomi et al. 2002, Nakamura et al. 2000, Benda et al. 2004,a).

By recognizing these themes, *TRIAD* is in accordance with principles embodied in new ecological perspectives including “riverscapes” (Ward et al. 2002, Fausch et al. 2002) and “hierarchical patch dynamics” (Wu and Loucks 1995, Poole 2002). These new perspectives are encouraging development of new methods to characterize habitat attributes at large, watershed scale, such as what is described in this manual.

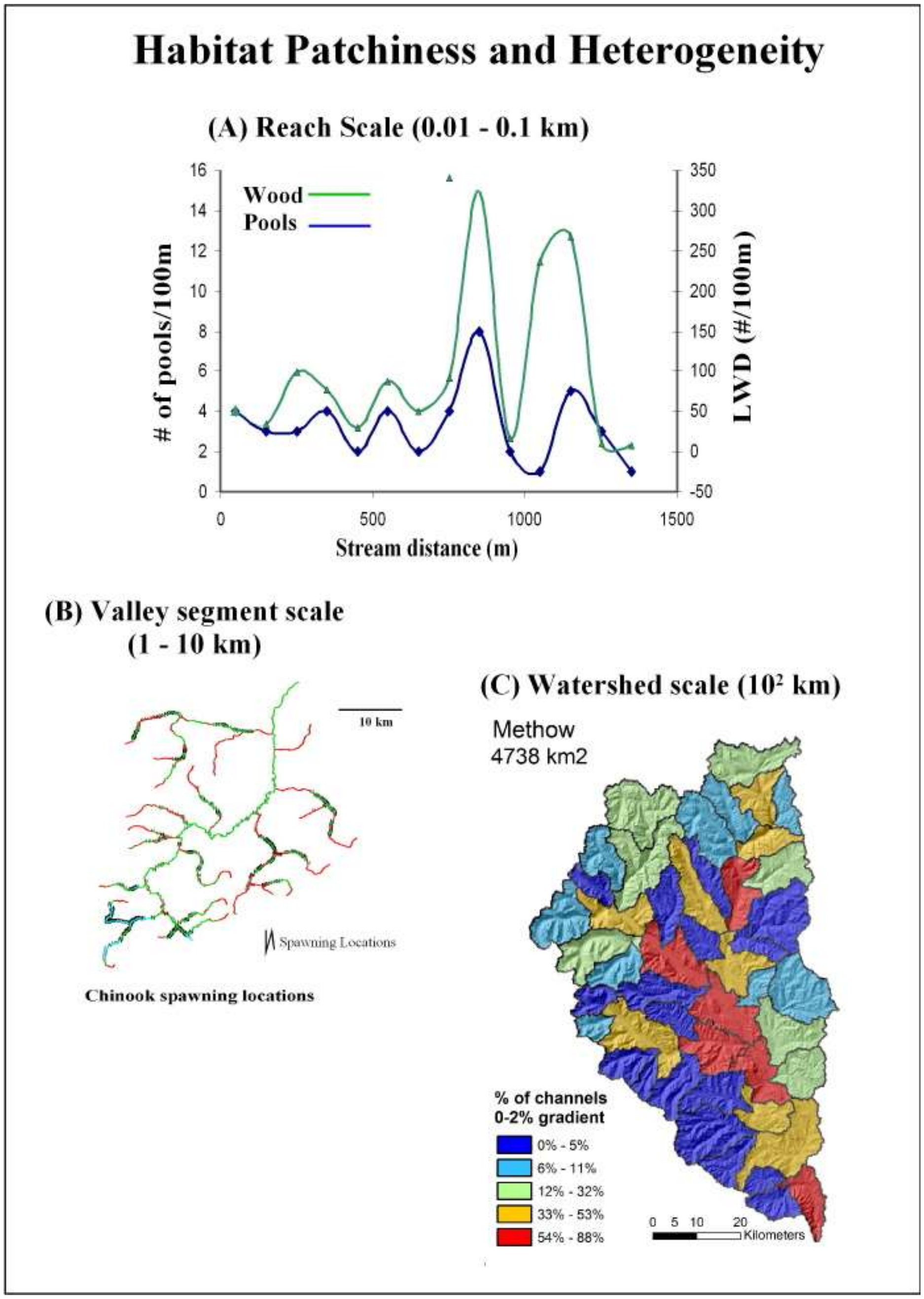

Figure 2. Habitat heterogeneity is driven by variations in topography, valley segments, and the structure of the drainage network, among other things. Habitat heterogeneity can occur at numerous scales, including reach (A), valley segment (B), and watershed (C). Understanding and identifying variations in habitat quality and abundance within individual watersheds and across population of watersheds is important in natural resource management planning, including restoration, monitoring, and conservation.

2.2 Spatial Scale, Analysis Detail, and the Value of Coarse Grain Information

The effort and cost required to study watershed attributes are dependent on the detail at which information is collected and analyzed. Detailed field surveys of landslides, channel morphology, and riparian forests encumber significant costs and time commitments. Although high levels of detail would appear desirable in environmental assessments, scientific uncertainty increases within interdisciplinary collaborations that pose complex environmental questions and that correspondingly collect detailed field measurements (Benda et al. 2002). For instance, the disciplines of geomorphology and riverine ecology are limited in their ability to make accurate predictions about complex watershed behavior, such as changes in channel morphology in response to increased bedload, or biotic response to changing channel conditions (Nilsson et a. 2003). Thus it is significantly more difficult to predict the changing volume of sediment in rivers due to landslides, or the response of stream biota to increased sediment supply, than it is to predict the location of potential landslides within a watershed or the locations of the intrinsically best habitats. Consequently, even when detailed quantitative physical and biological measurements are made during environmental assessments, unresolved complexity about watershed environments often causes decision-making to tend towards qualitative indices or professional judgments (O'Brien 2000).

Detailed field surveys in channels that occur during research programs are often focused at reach scales (10 – 1000 m). Measurement may include channel width, depth, pools, large wood, particle size, and vegetation age, among other things. Detailed field surveys generally do not occur at valley segment scales (1, 000 – 10,000 m) (e.g., "riverscapes", Fausch et al. 2002) because of practical limitations in time and funding (Figure 1). When analyses do occur at valley segment scales, or ever at larger watershed scales (such as during research programs or state and federal 'watershed analyses'), they describe more general characteristics such as overall channel/habitat types, valley segment types, and erosion potential, etc. (Baxter 2001, WDNR 1997).

Analyses of channel and watershed attributes relevant to riverine ecology and resource management at the landscape and state and regional scales are lacking because of the absence of terrain inventory databases at those scales and the software tools to manipulate them (Figure 1). *TRIAD* is designed to fill this gap by providing general quantitative descriptions of watershed attributes relevant to river ecology and resource management at scales that include valley segment (1,000 to 10,000 m), individual fish-bearing watersheds (100 – 1,000 km^2), landscapes (1,000 – 10,000 km^2), and states/regions (> 50,000 km^2). By necessity, the analysis of watersheds at landscape to regional scales must avoid detailed field measurements and historical analyses (time series) and instead focus on generalized quantitative descriptions of watershed and channel attributes utilizing digital topographic databases, other open-source databases, aerial photography, and limited field surveys (Figure 1).

TRIAD is not meant to replace other forms of more detailed and historical studies that might be necessary to address various environmental or natural resource-related questions. If necessary, information embodied in the terrain databases can be used to support more detailed analyses and it could also be integrated with information on land use patterns, etc.

2.3 Methodological Basis

The study of environmental conditions in watersheds should always be grounded in reality and hence have a strong field and aerial photograph component. This has been advocated for channel classification, habitat identification, wood loading in streams, and landslide occurrence, etc., even though the effort involved with field studies usually requires some form of sub sampling. However, the spatially continuous analysis of watershed environments, such as all stream channels in watersheds at landscape scales, requires some level of computer automation. Fortunately, concurrent with the advance of new concepts in riverine ecology is the vastly increased availability of digital topographic data and development of numerical techniques for inferring topographic and channel-network attributes. Algorithms for extracting surface gradient and curvature, contributing area, channel networks, and valley morphology allow inference of geomorphic processes and forms over entire watersheds (Miller 2005). *TRIAD* utilizes such models in combination with other traditional methods of mapping from aerial photographs and field recognizance. Guided by current conceptual frameworks in riverine ecology, and the coarse-grained approach for analysis of large, complex (watershed) systems, these tools are used to identify and characterize topographic, erosional, and fluvial controls on riverine habitats.

TRIAD provides information at two primary scales: (1) reach, valley segment, and individual hillslopes within a watershed and (2) populations of watersheds (Figure 3). At the

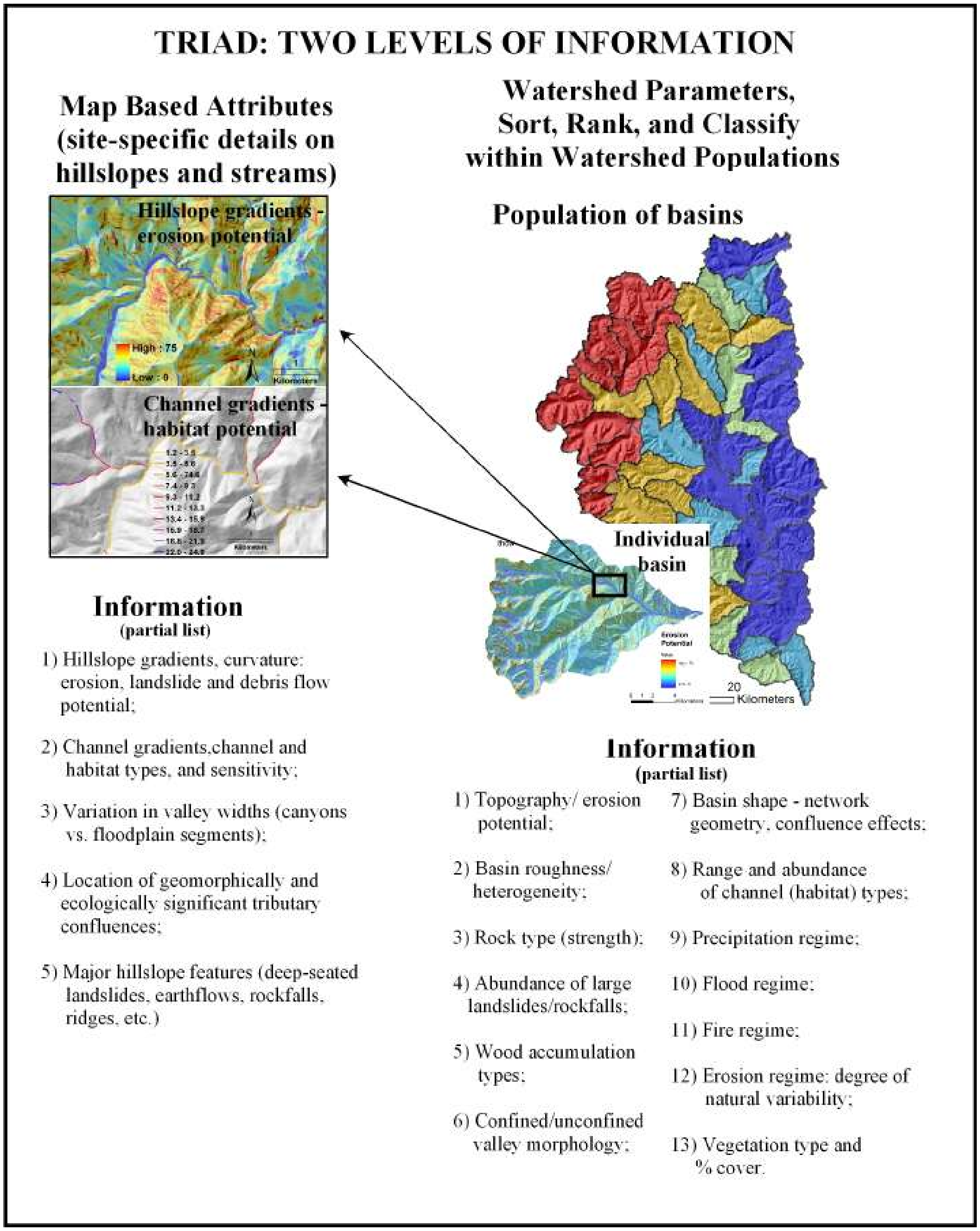

Figure 3. The Terrain Inventory and Analysis Database offers two levels of information. Map-based information (left panel) is useful for watershed- to valley segment-scale planning. Watershed parameter information (right panel) is comprised of cumulative distributions and single-value parameters covering numerous attributes of watersheds for cross-basin comparisons at the scale of landscapes, national forests, and regions.

smallest (pixel) scale set by DEM resolution, *TRIAD* maps the characteristics of individual hillslopes, valley segments, and stream reaches. This information can identify the juxtaposition of areas of high erosion potential with areas of high biological value and sensitivity, stable channel segments for monitoring, ecologically interesting geomorphic attributes of watersheds for planning restoration and conservation activities, and areas where intensive resource use may be feasible (Figure 3). The vast number of data contained in map-based information, however, precludes effective comparative analyses across watersheds. To create a queryable database for comparative analyses, a series of numeric watershed parameters are used to index the general nature and diversity of basin topography and riverine attributes. Parameters take the form of cumulative distributions functions (CDFs) of various watershed attributes and single values such as basin shape and basin topographic roughness, etc. Cumulative distributions are focused on larger streams and rivers such as the fish-bearing portion of networks (Figure 4). Use of numeric watershed parameters, such as CDFs, offers the ability to search, sort, compare, rank, and classify watershed attributes in populations (dozens to hundreds) of watersheds. *TRIAD* numeric parameters also can be used to create watershed classification systems. The two types of information are referred throughout the remainder of the manual as respectively “map-based attributes” and “watershed parameters” (Figure 3). Various basins in the United States. are used to illustrate the parameters.

Watershed attributes can be characterized over any basin scale. Most parameters in *TRIAD* are based on direct measurements; for example topographic parameters are calculated directly from a DEM (typically 10-m) although high resolution LIDAR can be used when available. A few parameters are estimated using empirical, regionally calibrated models. The appropriate basin scale over which to define watershed attributes depends on the objective of the analysis. For instance, hydrologic unit code (HUC) 5th- or 6th-field watersheds (100 - 1000 km^2) may be an appropriate scale of analysis for examining spatial variation in fish habitat types (and their genesis) and for considering various resource management questions.

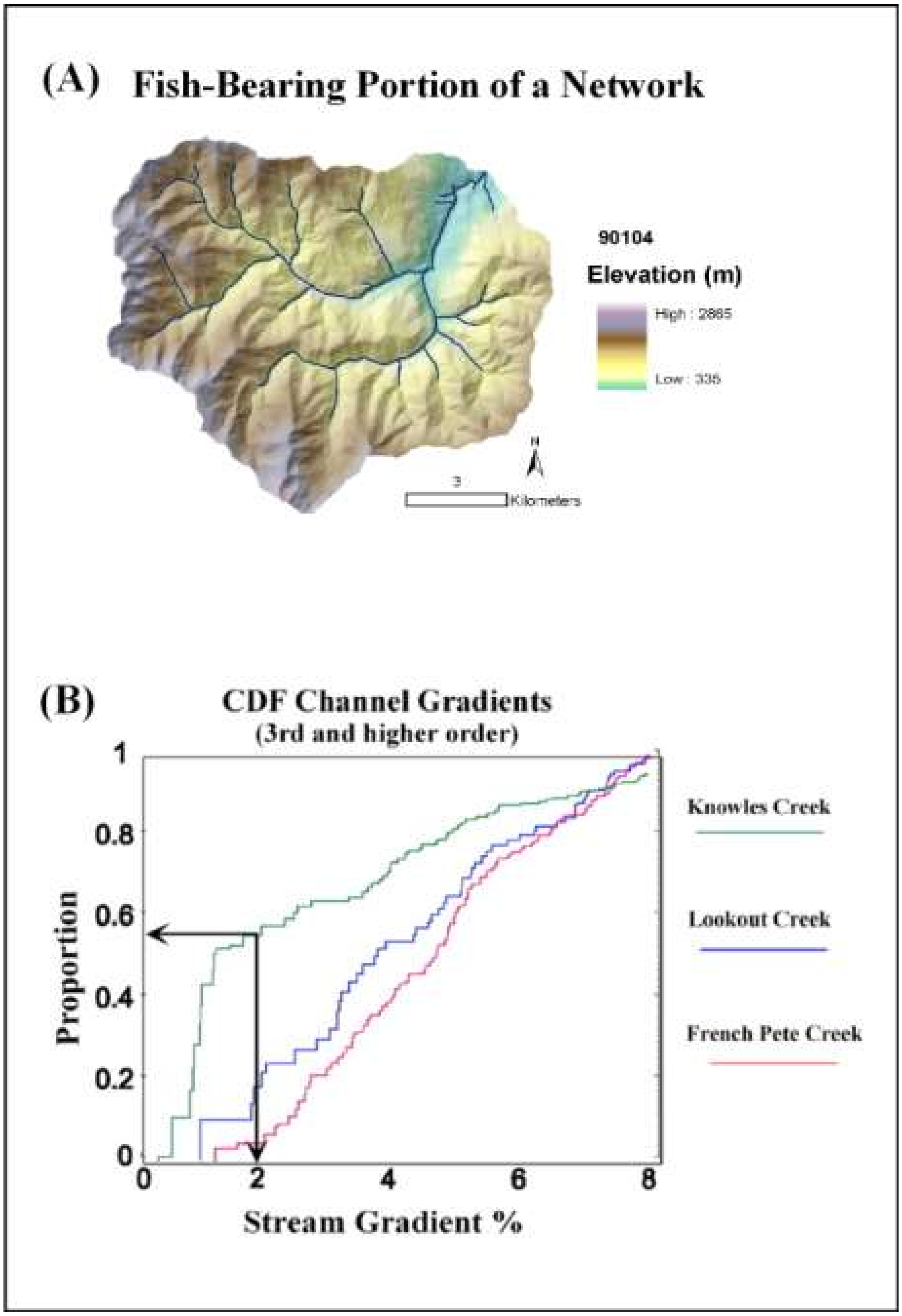

Figure 4. The lower-gradient and fish-bearing portions of channel network (A) are used to develop cumulative distribution functions (B). Approximately 70 to 80% of the channel network is comprised of steep headwater streams that would otherwise dominate the shape of the CDF. Variation in the abundance of low gradient channels is evident when comparing Knowles Creek basin (drainage area 50 km^2) in the central Oregon Coast Range with Lookout Creek basin (drainage area 63 km^2) and French Pete Creek basin (drainage area 83 km^2) in the central Oregon Cascade Range.

3. *TRIAD* PARAMETER DOMAINS

To simplify organization of the many factors involved in landscape – riverscape interactions, it is useful to separate watershed parameters into four domains: 1) hillslope topography and erosion processes, 2) valley morphology, river network configuration, and basin size, 3) channel and habitat types and response, and 4) climate-driven disturbance (Table 2). The first of these domains examines basin geology, hillslope topography, and large-scale erosion processes. The second domain examines valley morphology and structure of variation in valley confinement, the role of basin shape and channel network configuration on channel confluence types and effects, and the effects of basin size on the scale of habitat patches and heterogeneity. The third domain examines properties of channel morphology, including habitat types, wood accumulations, exposure to sediment, and sensitivity to change. The fourth and final domain examines the inter-relationships among hillslope topography, erosion potential, and habitat change by considering the importance of storm, flood, and fire regimes. Together, these four domains characterize the controls on habitat formation, habitat types and quality, and the ability of natural and land use disturbances to impact and alter river habitats. They provide essential information from the stream reach to regional landscape scales to inform natural resource management and conservation (e.g., Table 1). *TRIAD* also indexes basin connections (i.e., up- and downstream) such as other watersheds, lakes, reservoirs, estuaries, and closed basins.

3.1 First Parameter Domain: Basin Topography and Erosion

Stream channels exist in the context of their terrestrial environment, which includes erosional inputs from adjacent hillslopes and the constraints on channel form imposed by hillslope topography, including ridges, large landslides, debris flows, earthflows, rockfalls, and snow avalanches. Characterizing erosion processes in terrain analysis is important from two perspectives. First, valley floors are mantled in sediment eroded from basin hillslopes and thus erosional processes should be reflected in the types, diversity, and age distribution of sediment comprised in valley-floor riparian and fluvial landforms (Swanson et al. 1988, U.S.F.S. 2002, Benda et al. 1998). Second, land uses can accelerate erosion such as

Table 2 (A). A list of *TRIAD* parameters and whether they comprise *map based* or *queryable* watershed information, the latter in the form of cumulative distribution functions, single values, and plots. Parameters are organized according to four domains. [a] refers to specific landscapes, [1] to cumulative distribution functions, [2] to single values, and [3] to plots.

#	*TRIAD* Parameters	Map Based	Queryable Watershed Parameter (CDFs or single values)
	DOMAIN #1 (Topography and Erosion)		
1	Elevation/Relief	*	*[1]
2	Hillslope gradient	*	*[1]
3	Generic erosion potential	*	*[1]
4	Shallow landslide prediction [a]	*	*[1]
5	Debris flow prediction [a]	*	*[1]
6	Large landslides, earthflows, avalanches, rockfalls	*	*[2]
7	Bedrock outcrops		*[2]
8	Near channel roughness	*	*[1]
9	Whole basin roughness		*[2]
	DOMAIN #2 (Networks and Valleys)		
10	Drainage area/density		*[2]
11	Junction density		*[2]
12	Longitudinal profile		*[3]
13	Basin shape factor		*[2]
14	Tributary to Mainstem Drainage Area		*[1]
15	Confluence effects probability	*	*[1]
16	Confluence effects along mainstem	*	*[3]
17	Valley width	*	*[1,3]
18	Lengths of potential confluence effects	*	*[1]
19	Valley width index (VWI) (constrained, unconstrained, transitional)	*	*[1]
20	Proportion of reaches in wide (unconstrained) valleys	*	*[1,2]
21	Proportion of reaches in canyons	*	*[1,2]
22	Number of unconstrained valley segments	*	*[1,2]
23	Lengths of unconstrained valley segments	*	*[1,2]
24	Number of constrained valley segments	*	*[1,2]
25	Lengths of constrained valley segments	*	*[1,2]
26	Number/lengths of transitional segments: const-unconst; unconst-constr	*	*[1,2]
27	Proportions of various VWI indices		*[2]
28	Drainage area scaled habitat patch separation distance	*	*[1]
	DOMAIN #3 (Channel Type/Habitats and Sensitivity)		
29	Channel gradient	*	*[1]
30	Channel width	*	*[1]
31	Channel depth	*	*[1]
32	Channel type	*	*[1]
33	Site potential tree height (i.e., wood accumulation)	*	
34	Probability of wood accumulation types	*	*[1]

#	*TRIAD* Parameters	Map Based	Queryable Watershed Parameter (CDFs or single values)
35	Dominant wood accumulation type	*	*[1]
36	Cumulative sediment exposure	*	*[1]
	DOMAIN #4 (Climate and Disturbance)		
37	Climate types/precipitation regime		*[2]
38	Mean annual precipitation		*[2]
39	Flow regime		*[2]
40	Mean annual flow		*[2]
41	Fire regime		*[2]
42	Erosion regime		*[2]
43	Regulated rivers		*[2]
44	Vegetation	*	*[2]
45	Estuary character		*[2]
46	Open (0) or enclosed (1) basin		*[2]
47	Other basin connections		*[2]

Table 2 (B). A list of *TRIAD* parameters showing the hierarchy of informational sources (1-primary, 2-secondary, 3-tertiary) and where validation (v) is recommended. Parameters are organized according to four domains. [a] refers to specific landscapes.

#	TRIAD Parameters	DEMs-Computer Model	Aerial Photography	Field Reconnaissance	Other Studies
	DOMAIN #1 (Topography and Erosion)				
1	Elevation/Relief	1			
2	Hillslope gradient	1			
3	Generic erosion potential	1	2	2	v
4	Shallow landslide prediction [a]	1	2	3	v
5	Debris flow prediction [a]	1	2	3	v
6	Large landslides, earthflows, avalanches, rockfalls	1(opt.)	1	2	
7	Bedrock outcrops		1	2	
8	Near channel roughness		2	2	
9	Whole basin roughness	1			
	DOMAIN #2 (Networks and Valleys)				
10	Drainage area/density	1			v
11	Junction density	1			v
12	Longitudinal profile	1			
13	Basin shape factor	1			
14	Tributary to Mainstem Drainage Area	1			
15	Confluence effects probability	1	2	2	v
16	Confluence effects along mainstem	1	2	2	v
17	Valley width	1	2	2	v
18	Lengths of potential confluence effects	1	2	2	v
19	Valley width index (VWI) (constrained, unconstrained, transitional)	1	3	2	
20	Proportion of reaches in wide (unconstrained) valleys	1	2(v)		
21	Proportion of reaches in canyons	1	2(v)		
22	Number of unconstrained valley segments	1	2(v)		
23	Lengths of unconstrained valley segments	1	2(v)		
24	Number of constrained valley segments	1	2(v)		

#	TRIAD Parameters	DEMs-Computer Model	Aerial Photography	Field Reconnaissance	Other Studies
25	Lengths of constrained valley segments	1	2(v)		
26	Number/lengths of transitional segments: const-unconst; unconst-constr	1	2(v)		
27	Proportions of various VWI indices	1			
28	Drainage area scaled habitat patch separation distance	1	2(v)	v	
	DOMAIN #3 (Channel Type/Habitats and Sensitivity)				
29	Channel gradient	1	2(v)	2(v)	v
30	Channel width	1	2(v)	2(v)	v
31	Channel depth	1	2(v)		2(v)
32	Channel type	1	1	1	v
33	Site potential tree height (i.e., wood accumulation)	1	3	1	v
34	Probability of wood accumulation types	1			
35	Dominant wood accumulation type	1	2	1	v
36	Cumulative sediment exposure	1	2	2	v
	DOMAIN #4 (Climate and Disturbance)				
37	Climate types/precipitation regime				1
38	Mean annual precipitation				1
39	Flow regime				1
40	Mean annual flow				1
41	Fire regime				1
42	Erosion regime	2	2	2	1
43	Regulated rivers		2	2	1
44	Vegetation		2	2	1
45	Estuary character		1	1	v
46	Open (0) or enclosed (1) basin	1			
47	Other basin connections	1			v

landsliding (Sidle et al. 1985) with consequent impacts to aquatic systems (Everest et al. 1987). In *TRIAD*, basin attributes that characterize erosion are used to consider the role of sediment inputs on formation of riverine habitats and their sensitivity to land use. However, the relationship between erosion and river habitats requires using information available in the other domains including climate, vegetation, and channel sensitivity to change.

With the advent of digital elevation data, computer-based numerical analyses can readily characterize basin topography. *TRIAD* examines the role of topography and erosion processes on riverine habitats using the following parameters: 1) generic erosion potential using hillslope gradient and curvature, 2) shallow landslide potential (for specific landscapes), 3) debris flow potential (for specific landscapes), 4) large landslides, earthflows, rockfalls, and snow avalanches, 5) stream-adjacent topographic roughness (ridges, rockfalls), 6) mean basin topographic roughness, and 7) rock type and rock strength. Each of these is described in turn below.

3.1.1 Generic Erosion Potential: Hillslope Gradient and Curvature

Hillslope gradient fundamentally controls erosion type and magnitude (Dunne and Leopold 1978) (Figure 5). For instance, in humid environments the highest density of shallow failures due to heavy precipitation occurs on slopes in excess of approximately 35° (> 72%) (Dragovich et al. 1993). Hillslope gradient is also a factor controlling the location of gully erosion that often occurs following fire in some landscapes; erosion is generally more intense on steeper slopes (Istanbullouglu et al. 2003). Surface erosion occurs on more gentle terrain, although its magnitude is directly proportional to slope gradient (Elliot et al. 2000).

The morphological form of hillslopes that is related to erosion is often classified into several types, including convergent, divergent, and planar (Figure 6, A). Convergent areas, also referred to as swales, bedrock hollows, and zero-order basins, focus the transport of sediment and water. Over time (centuries), soil creep causes soils to thicken in convergent areas making them more susceptible to landsliding (Sidle 1987). During storms, convergent areas also focus shallow subsurface flow thereby increasing saturation and making them more susceptible to failures. Convergent areas also concentrate overland flow making them focal areas for gully development, particularly after fire. Steep convergent areas in humid

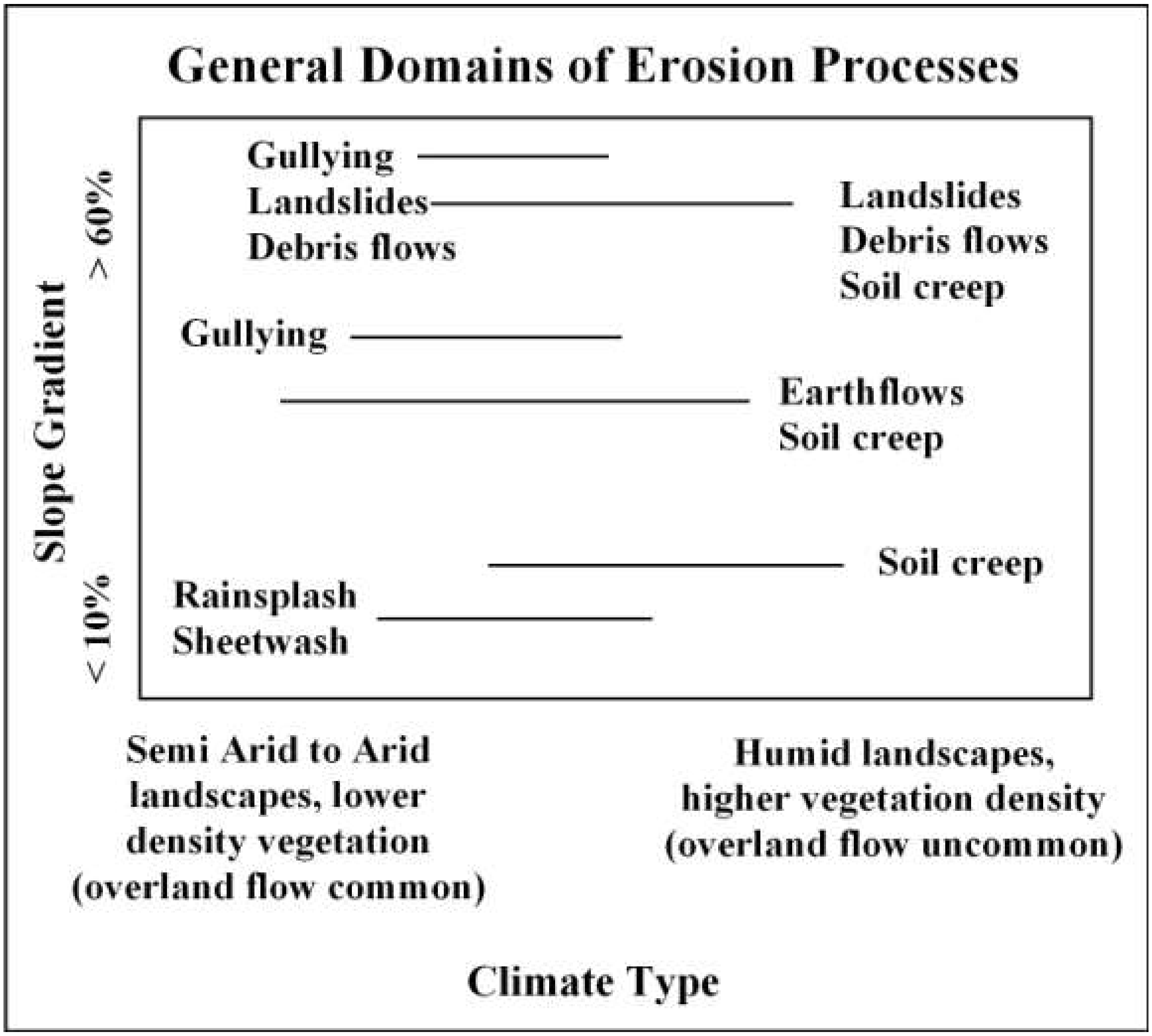

Figure 5. Hillslope gradients strongly influence the type of erosion that characterizes semi-arid to humid landscapes (adapted from Figure 15-1 of Dunne and Leopold [1978]).

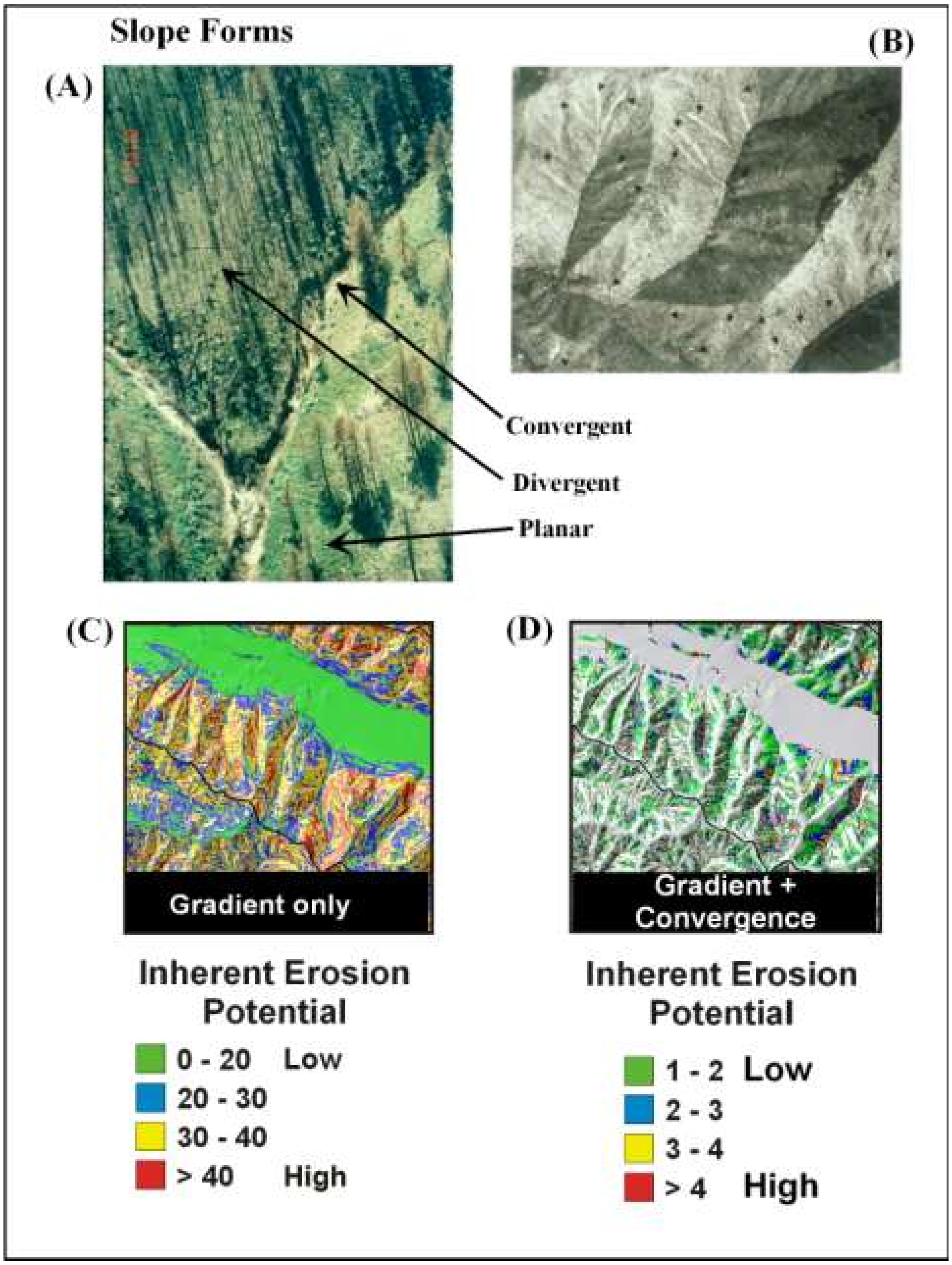

Figure 6. Steep, convergent areas in many landscapes are prone to various forms of erosion including (A) gullying in semi-arid areas, particularly following fires and (B) shallow failures in humid landscapes. Hillslopes can be categorized into (A) convergent, divergent, and planar forms. Slope gradient alone (C) can be used as an approximate indicator of erosion potential since all forms of erosion are strongly governed by slope. A more accurate predictor of erosion potential is slope combined with some measure of topographic convergence to create a generic or intrinsic index of erosion potential (D).

landscapes also are a major initiation point for debris flows in low-order streams (Dietrich and Dunne, 1978) (Figure 6, B).

To estimate the intrinsic erosion potential of a watershed, *TRIAD* generates maps of hillslope gradient, and maps of gradient combined with curvature, the latter an erosion index (Figure 6 C, D). The generic erosion index employs a combination of slope gradient and local topographic convergence given by $(A_L*S)/b$, where b is a measure of local topographic convergence (the length of an elevation contour crossed by flow out of the pixel, values less than one pixel length indicate convergent topography), A_L is a measure of local contributing area (within one pixel length), and S is slope gradient (Miller and Burnett in review, Miller 2005). When compared to an extensive landslide inventory in the Oregon Coast Range (Robison et al. 1999, Bush et al. 1997), the index function performed better than hillslope gradient alone or other landslide models.

The generic erosion index is applicable to any landscape since steep, convergent areas are preferential locations for many forms of erosion (e.g., Figure 6 A, B). However, erosion potential should be considered only in the context of additional information on climate and vegetation, parameters that are discussed later. For example, steep and convergent areas in humid landscapes are more susceptible to shallow landslides and debris flows during heavy rain and rain-on-snow compared to similar landforms in semi-arid landscapes where convergent landforms may pose less of an erosion hazard due to gradual spring snowmelt runoff, with the exception of post-fire gullying.

In addition to map-based erosion predictions, *TRIAD* employs a 'watershed parameter' of erosion - a cumulative distribution function (CDF) of hillslope gradients (Figure 7) or a CDF of the generic erosion index that can be queried using the *watershed database software interface* (outlined in 4.1 and described in Part 2 of the manual). The CDF identifies the proportion of watershed area susceptible to certain types of erosion (an interpretation conditioned by fire and precipitation regimes, etc.). For example, the proportion of the slope gradient CDF greater than 35^o ranges from 0% to 15% across the example basins shown in Figure 7. Hence, the CDF measures a range of intrinsic erosion potentials. Heterogeneity of hillslope gradients reflected in a CDF (the spread of the distribution) also can reflect the diversity of erosion processes and hence the diversity of erosion rates within a basin. The CDF is used within a queryable database from which watersheds can be ranked with respect to inherent erosion potential (see Section 4.0).

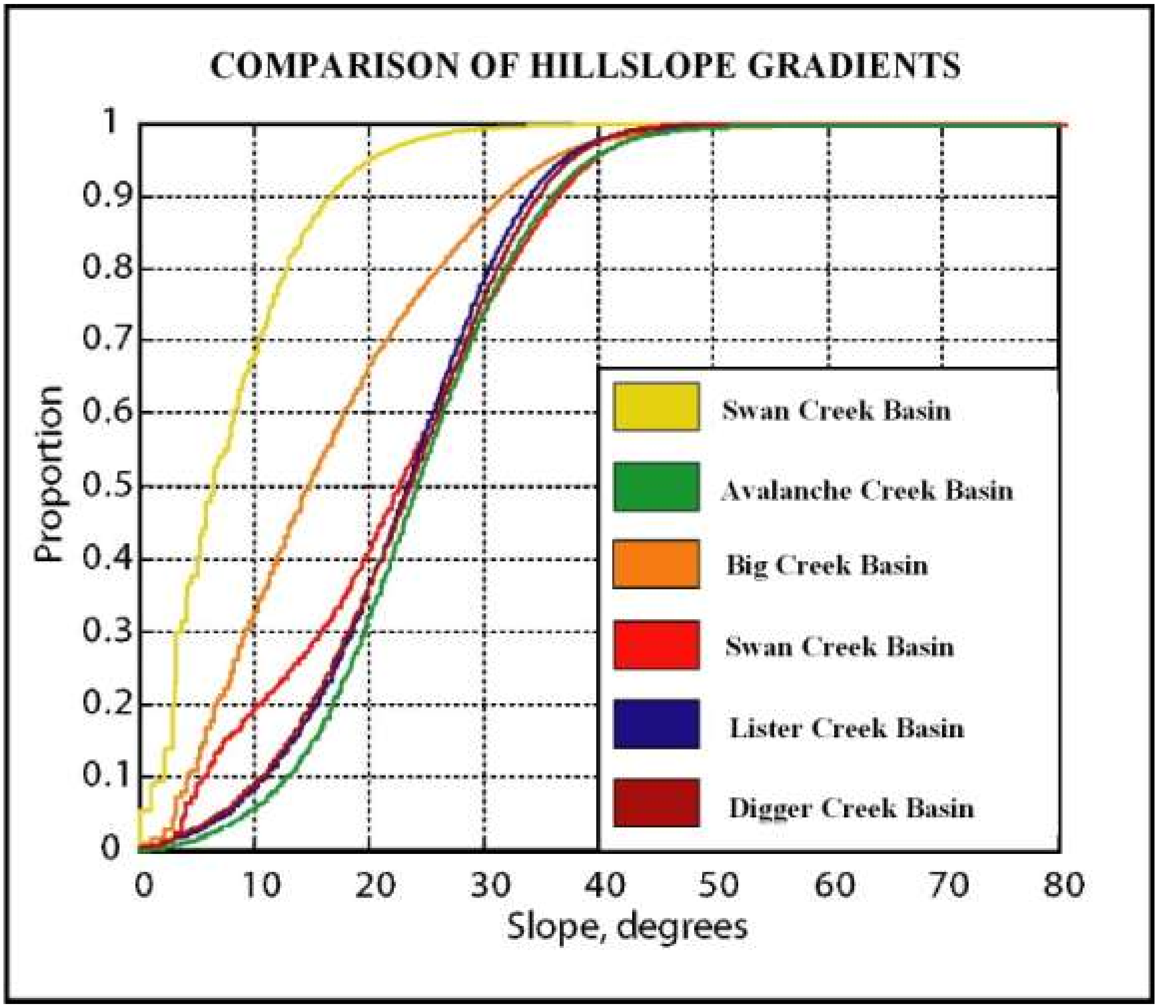

Figure 7. Creating CDFs of erosion indices such as gradient or gradient in combination with convergence allows for sorting and ranking erosion potential across a populations of watersheds for cross basin comparisons.

3.1.2 Empirically Calibrated Landslide Model for Specific Landscapes

There are a variety of models available to predict shallow landslides, primarily for humid mountain landscapes (Sidle 1987, Montgomery and Dietrich 1994, Pack et al. 1998). Most models require information on hillslope topography, including gradients and some measure of convergence. In *TRIAD*, the generic erosion index described in the previous section is calibrated using digitized landslide inventories from the Oregon Coast Range (Robison et al. 1999, Bush et al. 2000) from which landslide density (e.g., number of landslides per unit area, or area of landslides per unit area) is determined as a function of topographic and vegetation attributes (Miller and Burnett in review and Miller 2005). The model utilizes 25-m satellite imagery of forest vegetation (Ohmann and Gregory 2002) that affects landslide density (Figure 8). Younger forests (post clearcut harvest) yield higher landslide rates because of the lower rooting strength compared to mature forests. Calculations are made at the resolution of the 10-m DEM, which for available USGS-provided data, reflects 40-foot contours mapped at 1:24,000 scale. Because of the empirical calibration, the model is best suited for coastal Oregon, although it should have applications for other humid mountain landscapes that are prone to shallow failures concentrated in steep and convergent areas.

Topographic information provided by 1:24,000 scale mapping does not resolve all topographic features pertinent to landslide locations (Benda and Dunne 1997). For instance, the landslide model does not account for small streamside failures (often referred to as inner gorge landslides) because of the inability of 10-m DEMs to resolve low relief landforms. Mapped landslide potential (e.g., Figure 8) may also not resolve all small convergent areas, important to project level site-specific assessments. However, mapped landslide potential resolves topographic controls over larger areas, such as the relative risk between different first-order basins or between larger watersheds.

Individual landslide sites in the landslide inventory were geo-spatially referenced on 10-M DEMs and hence the slope gradients associated with failure sites were derived from the DEM (and not from the field measurements) since the goal was to develop a model that utilized a digital database. Consequently, the predicted locations of potential landslide sites (indexed by a variable landslide density) may occur on lower gradient areas (on the DEM), compared to what may be found in the field. In other words, 10-m DEMS commonly

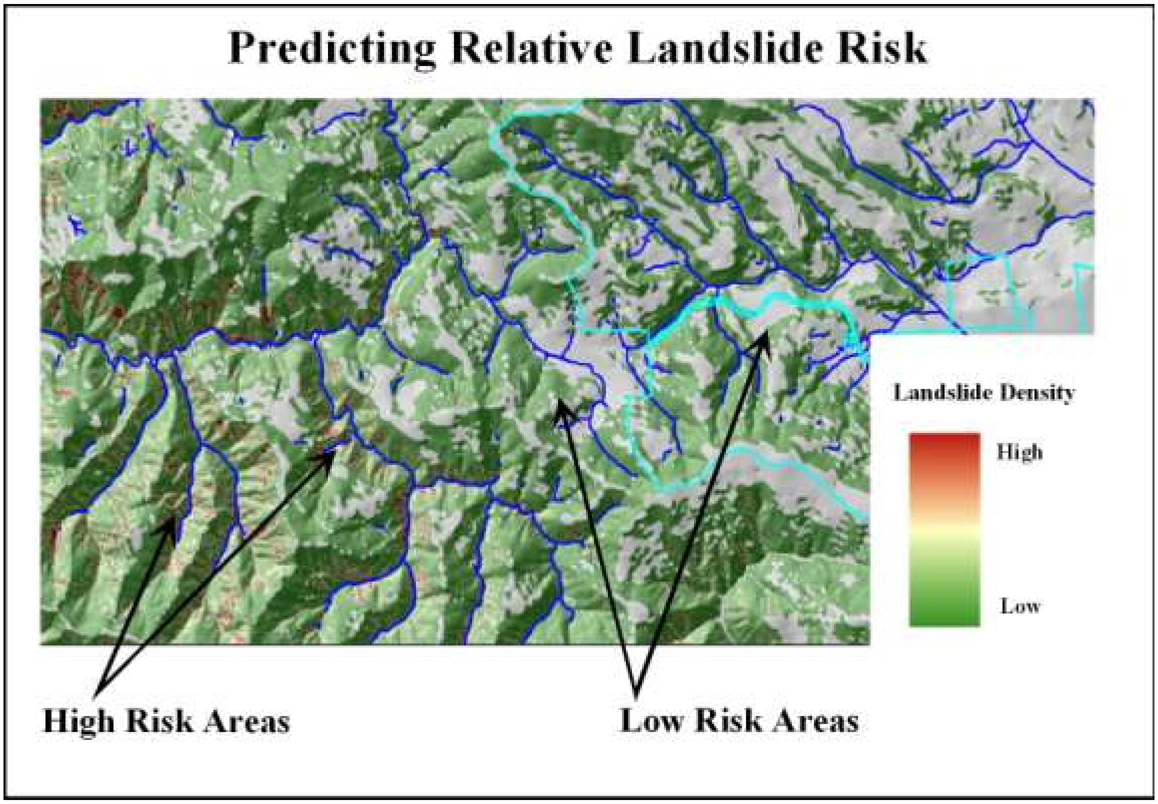

Figure 8. Empirically calibrated models for shallow landsliding can be applied to specific landscapes. The model shown here was developed for the Oregon Coast Range, although it is likely applicable to a wider geographic area in humid mountainous terrain.

underestimate slope gradients. Hence, it is not appropriate to contrast a DEM-based slope gradient map with the predicted landslide density index to compare or contrast slide potential (i.e., Figures 6 and 8). A slope map can be used as a stand- alone measure of erosion potential, with the understanding that 10-m DEMs underestimate slope gradients. Likewise, the 10-m DEM-based landslide density predictions are a stand-alone representation of shallow failure potential, although the slope gradients associated with failure (on the DEM) are likely less than the gradients that would be measured at those locations in the field.

3.1.3 Empirically Calibrated Debris Flow Potential for Specific Landscapes

There are a variety of models developed to predict debris flows and their movement and deposition in headwater streams primarily in humid landscapes (Benda and Cundy 1990, Hungr et al. 1984, Fannin and Rollerson 1993, Lancaster et al. 2001). Most of these models require information on network characteristics of headwater systems such as channel gradients and tributary junction angles.

Similar to the empirically calibrated landslide model, predictions of debris flows in *TRIAD* are based on four topographic attributes derived from field studies in the Oregon Coast Range (using data from Robison et al. 1999) and include 1) channel slope, 2) valley width or confinement, 3) angles of tributary junctions, and 4) cumulative length of scour and deposition (i.e., rate of volume increase or decrease) (refer to Miller et al. 2003, and Miller and Burnett in review). In the model, debris flow runout is separated into zones of scour, transitional flow, and deposition. The functional relationships between debris flow scour and deposition and the four topographic factors are based on field research that has illustrated the physical constraints on debris flow travel. For example, debris flow movement declines with decreasing channel slope (Swanson and Lienkaemper 1978, Benda and Cundy 1990, Fannin and Rollerson 1993, Fannin and Wise 2001), declines at sharp-angled tributary junctions (Benda and Cundy 1990), is less in large forests and longer in clearcuts (Ketcheson and Froelich 1978, May 2002), and increases with larger volumes (Benda and Cundy 1990). Because of the empirical calibration, the debris flow model is most appropriate for coastal Oregon, although it could be applied to other humid mountain landscapes that are prone to debris flows in steep headwater streams.

Debris flow runout is sensitive to forest cover with higher probabilities of debris flows associated with open (clearcut) cover compared to mature forests based on the empirical data used to calibrate the model. This is because mature forests are associated with fewer field observations of debris flow scour, more deposition, and shorter runout paths. This finding is consistent with previous studies of debris flow movement in the Oregon Coast Range (Ketcheson and Froelich 1978, May 2002).

Model predictions take various forms including probability of a debris flow in any specific channel segment, the probability of delivery of sediment and wood to fish-bearing streams, and maximum runout length. Only the probability of debris flows is shown in Figure 9 (Figure 9, A) as a mapped-based attribute. Cumulative distributions of debris flow probabilities (Figure 9, B) for a given watershed provides a watershed parameter that can be used to sort and rank the overall potential of debris flow risk or to create maps of cumulative debris flow potential at subbasin scales (Figure 9, C).

3.1.4 Large Landslides, Earthflows, Rockfalls, and Snow Avalanches

Large and ancient landslides, earthflows, and rockfalls can be considered either as a threat to aquatic resources or as a source of habitat formation depending upon ecological perspective. Because large landslides occur relatively infrequently, the majority of such features in a watershed should be old and hence could be viewed as sources of physical heterogeneity in rivers by creating knick points that reduce valley gradient upstream and increase gradients downstream (Grant and Swanson 1995, Cruden and Thomson 1997). Lower-gradient valley segments upstream of large slides can create wide valleys containing more floodplains, side channels, and more sediment and woody debris (Figure 10). In landscapes such as the central Oregon Cascade Range, earthflows are numerous and important sources of physical heterogeneity in mountain stream channels, including forming local floodplain habitats (Figure 11) (Grant and Swanson 1995).

Snow avalanches and rockfall-generated talus can also be important point sources of sediment and wood to streams and rivers and the depositional fans they create can function similarly to debris flow fans or alluvial fans in receiving streams. Snow avalanches can force channel meandering, create openings in riparian forests, and lead to increased bar

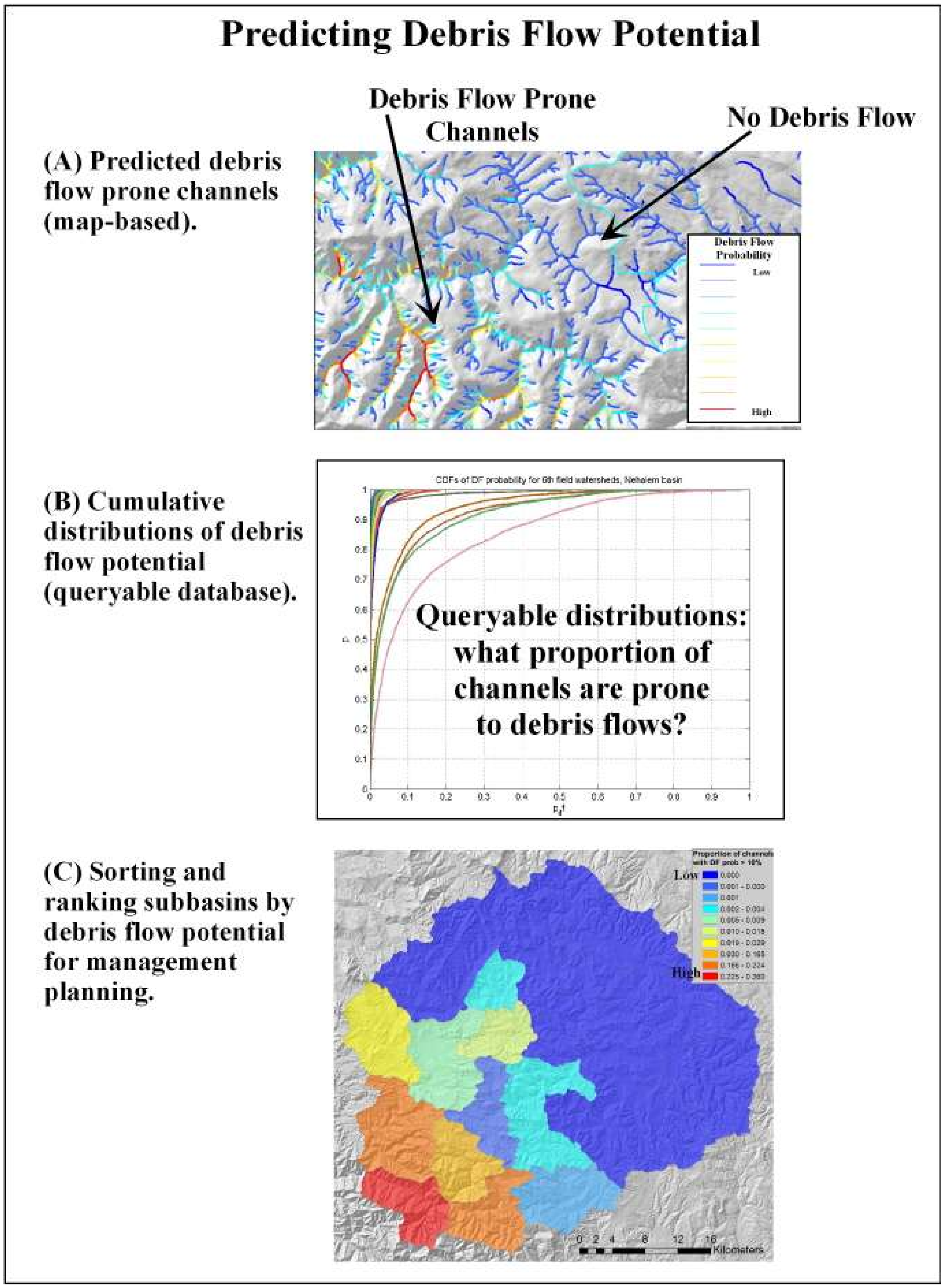

Figure 9. Models for debris flows can be applied to specific landscapes. The model shown here was developed and empirically calibrated for the Oregon Coast Range. (A) Maps are produced indicating the locations of varying potential for debris flows at the individual hillslope scale. (B) Cumulative distribution functions (CDFs) of relative debris flow risk are created at the subbasin scale. Such information can be used to sort and rank subbasins according to debris flow risk across landscapes (C). The model should have general applicability to other landscapes prone to debris flows.

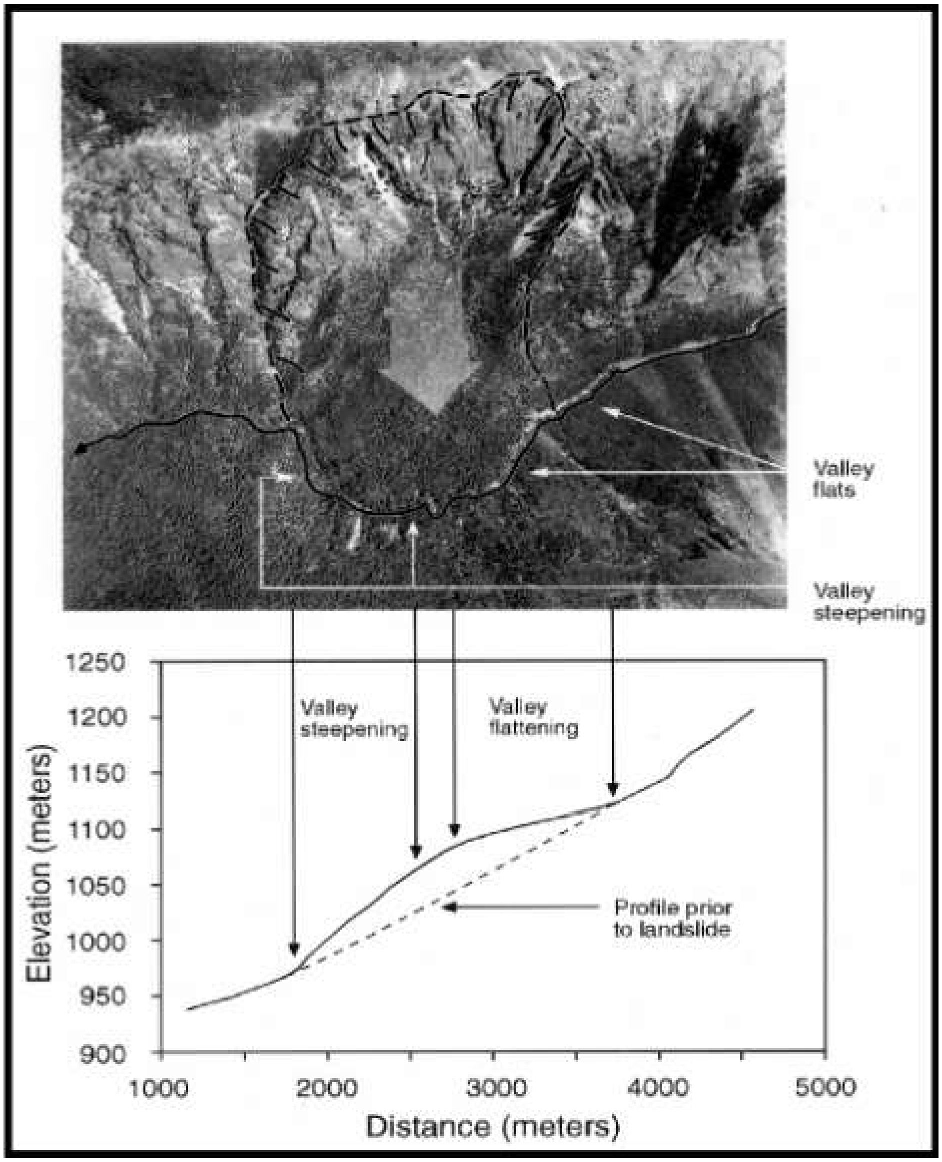

Figure 10. Large, ancient deep-seated landslides can be a source of habitat development and heterogeneity. The landslide depicted here, located in eastern Washington, has resulted in a large bulge in the longitudinal profile of the river. Upstream of the landslide low gradient valleys and channels have created floodplains and lower gradient, meandering channels. Younger deep-seated landslides can pose a threat to aquatic resources through increased erosion and turbidity. Because of the rarity of large landslide events, the majority of such features in a watershed should be old.

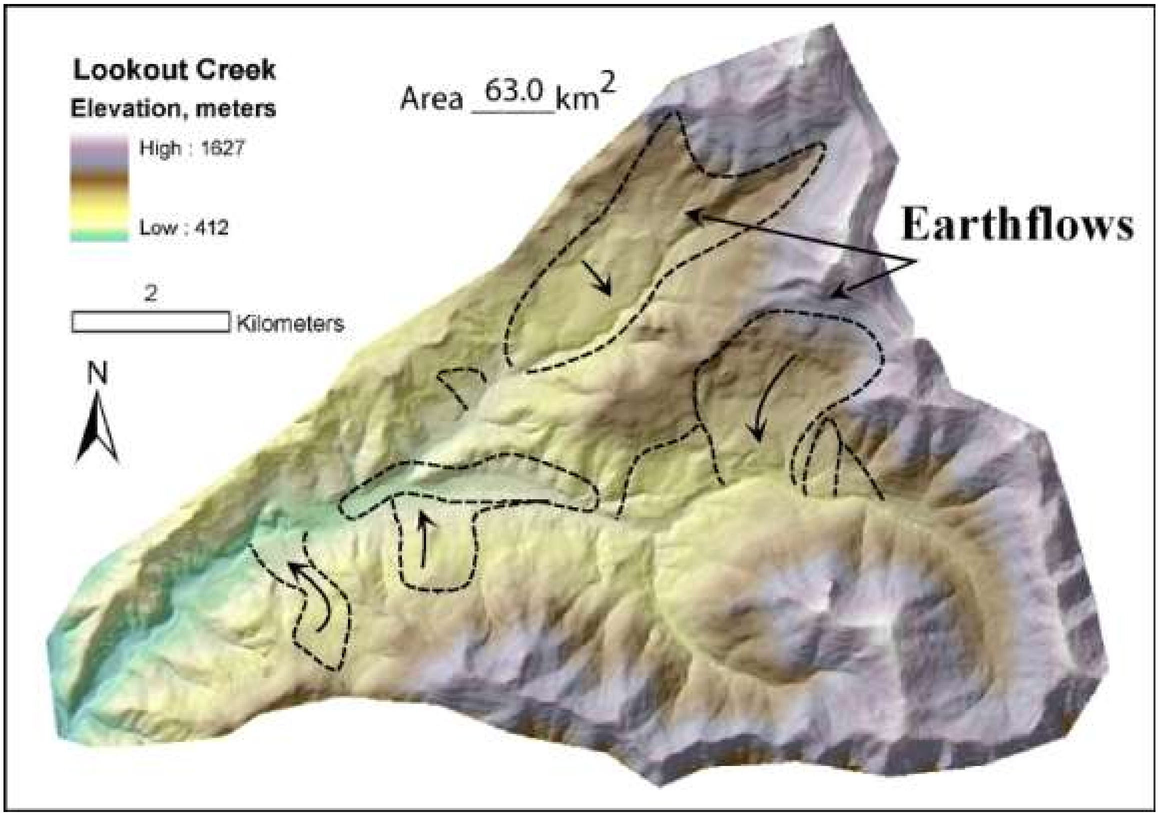

Figure 11. Large landslides and ancient earthflows are numerous in many mountain landscapes such as in certain parts of the Oregon Coast Range (Roering et al. 2005), southwest Washington (Dragovich et al. 1993) and shown here in the central Oregon Cascades (Grant and Swanson 1995). Such landslides may be important sources of riverine heterogeneity (e.g., Figure 10)

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formation (Figure 12). However, the relationship of snow avalanches to river habitats is poorly understood.

Large landslides and earthflows also can be considered detrimental to rivers because of increased sedimentation including fine sediment, direct burial of aquatic habitats, and temporary blockages to fish migration. Overall, the morphological consequences of large and ancient landslides, earthflows, rockfalls, and snow avalanches on river channels are poorly understood. The occurrence of large mass wasting features in watersheds can be demarcated on maps (e.g., Figure 11), although aerial photography and field surveys may be necessary to detect them. Computer models also can also be used to predict their location in some landscapes (Roering et al. 2005). Large mass wasting features can be indexed using a single parameter that describes landslide abundance in a watershed either qualitatively (i.e., many, few, none) or quantitatively, such as landslide density (#/area). Various landslide classification schemes can be used for differentiating among the mass movement types (e.g., Cruden and Varnes 1996), as well as their ages (e.g., recently active versus dormant etc.).

3.1.5 Stream-Adjacent Topographic Roughness: Topographic Influences in Channels

Near stream topography, such as ridges and bedrock outcrops, can strongly influence local channel and valley morphology. For instance, ridges that intersect streams or bedrock outcrops that emerge close to channels can create falls and rapids, increase sediment storage, and form pools (Figure 13). Steep bedrock near streams can also lead to rockfalls and talus that impacts local channel morphology.

Local topographic controls on channel morphology in *TRIAD* are gauged using a measure of topographic roughness or variability in surface gradient within a specified area adjacent to each channel. The measure of local roughness is calculated using the difference between hillslope and channel gradients within a specified radius from the channel; the radius over which roughness is calculated is defined in terms of channel widths. Topographic roughness for each grid cell is calculated by taking the average of the elevation differences among its neighboring cells (squared and then square rooted to create positive values, referred to as the root-mean-square). Measures of topographic roughness are sensitive to the resolution of elevation data and the scale over which it is measured.

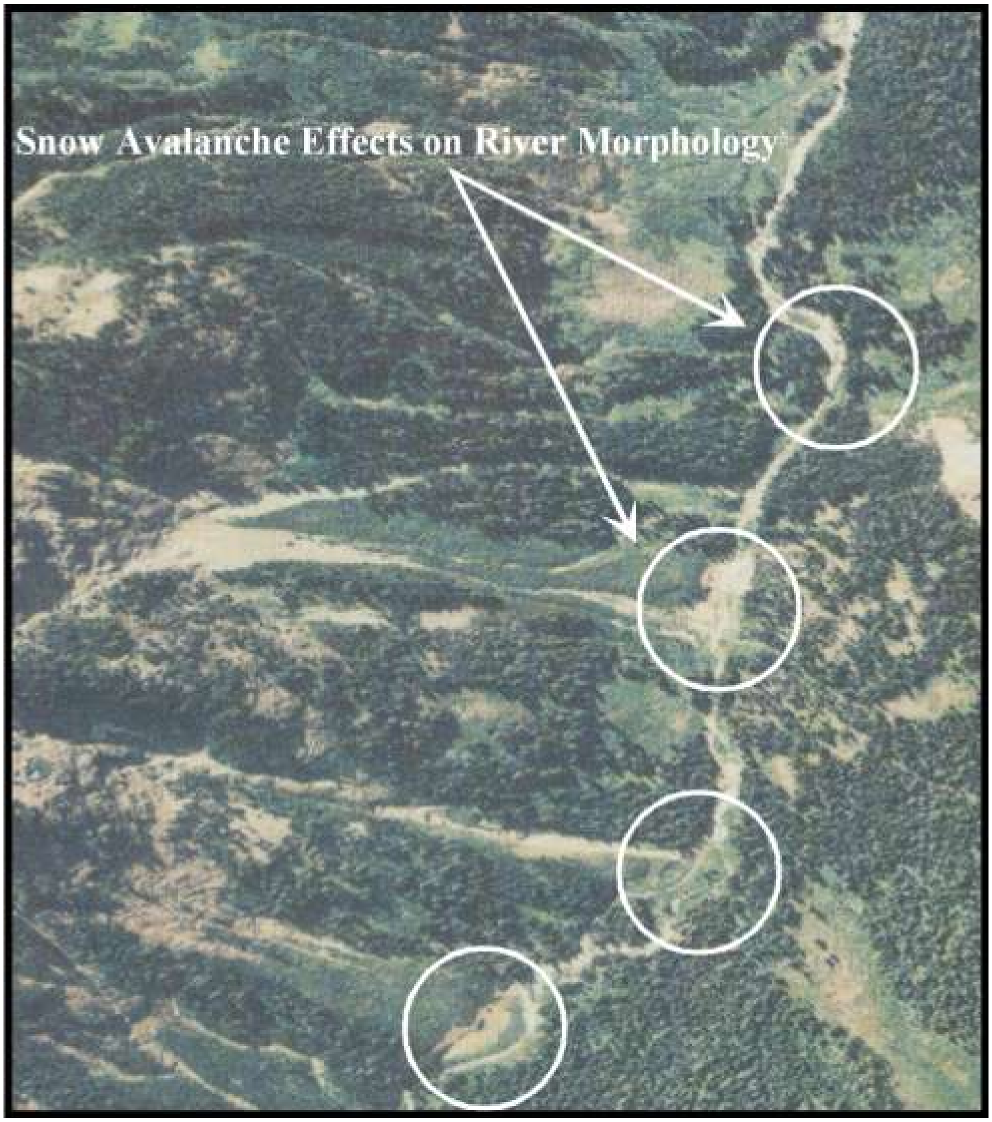


Figure 12. Snow avalanches are effective transporters of sediment and woody debris into many streams in high elevation mountainous terrain, for example, in the upper Wenatchee River basin, eastern Washington. Morphological impacts can include channel widening, increased bar formation, increased channel meandering, and riparian openings. Photo from Hessburg, et.al., 1999.

Figure 13. Some river systems have significant bedrock controls on river form as shown in the upper Umpqua River in the Oregon Cascades. Measures of stream-adjacent topographic roughness (Figure 14) combined with geology (rock strength) can be used predict their likely occurrence. Aerial photographs and ground surveys can also be used to register their importance for fluvial geomorphology and aquatic habitats.

High values of stream-adjacent roughness indicate the potential for lateral topographic controls on channel morphology (topographic hard points, ridges and bedrock outcrops) including increased supply of coarse sediment from rockfalls to the channel (Figure 14). Application of this simple approach indicates that there is significant spatial variability in stream-adjacent topographic roughness across watersheds with implications for aquatic habitats (Figure 15).

3.1.6 Basin-Averaged Topographic Roughness: General Index of Topographic Heterogeneity

Basin-averaged topographic roughness can provide information on the overall steepness and diversity of hillslope gradients within a watershed. Basin scale topographic roughness can relate to terrestrial habitat heterogeneity (Koehler and Hornocker 1989, Fabricius and Coetzee 1992) and potentially to riverine habitat diversity (Benda et al. 2004,a). Topographic roughness is calculated by measuring the difference in surface gradient from a DEM grid cell to its neighboring cells, similarly to the near-stream topographic roughness. Using 10-m DEMs, topographic roughness can vary from one watershed to another (Figure 16) and it ranges from a low of < 10 on relatively gentle and smooth topography to over 50 in rugged mountain ranges. Topographic roughness should also vary with respect to drainage density and the density of swales or convergent areas in a watershed, although this relationship is not well documented. In the example shown in Figure 16, the higher roughness of the Mayemes River basin (Luquillo LTER, Puerto Rico) should translate into a greater degree of physical diversity in the channel and valley floor driven by tributary confluences, alternating canyons and floodplain segments, large landslides, and bedrock outcrops compared to the Kuparuk River basin (Arctic LTER, north slope of Alaska).

3.1.7 Geology: Rock Type, Strength and Other Surficial Materials

Basin geology described by rock type (lithology) and structure (faults, dikes, etc.) are fundamental controls on many watershed attributes, including relief, hillslope steepness, erosion processes, network geometry, substrate size in channels, and water quality. The first five of these parameters are covered elsewhere in *TRIAD*. However, the geology of a watershed with respect to rock type can favor the generation of high suspended-sediment loads and turbidity (i.e., mudstone and siltstone), a factor that has implications for assessing

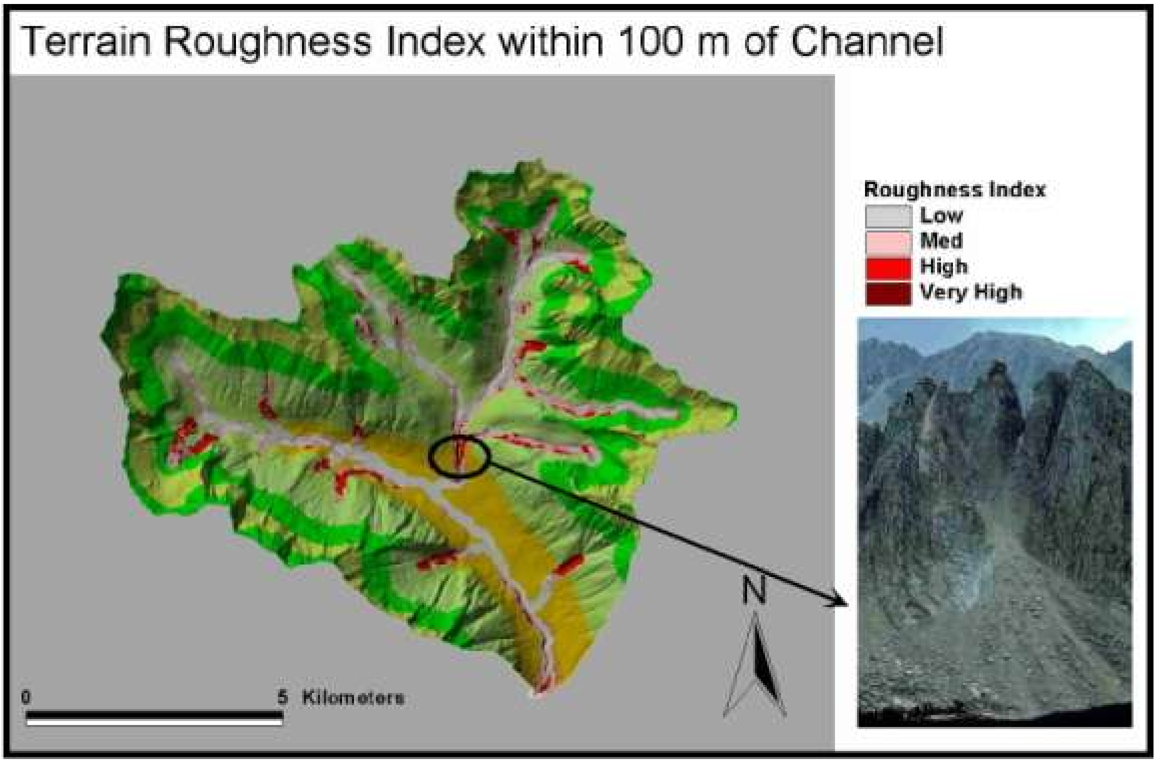


Figure 14. Stream-adjacent topographic roughness can indicate the occurrence of topographic forcing on river morphology including ridges, bedrock outcrops, rockfalls, and talus. Such controls can lead to certain types of river morphology. Stream-adjacent topographic roughness can vary spatially in a watershed contributing to riverine heterogeneity. River habitats associated with high topographic roughness (e.g., ridges, bedrock outcrops, and rockfalls) may be more resistant to both natural disturbance and human impacts.

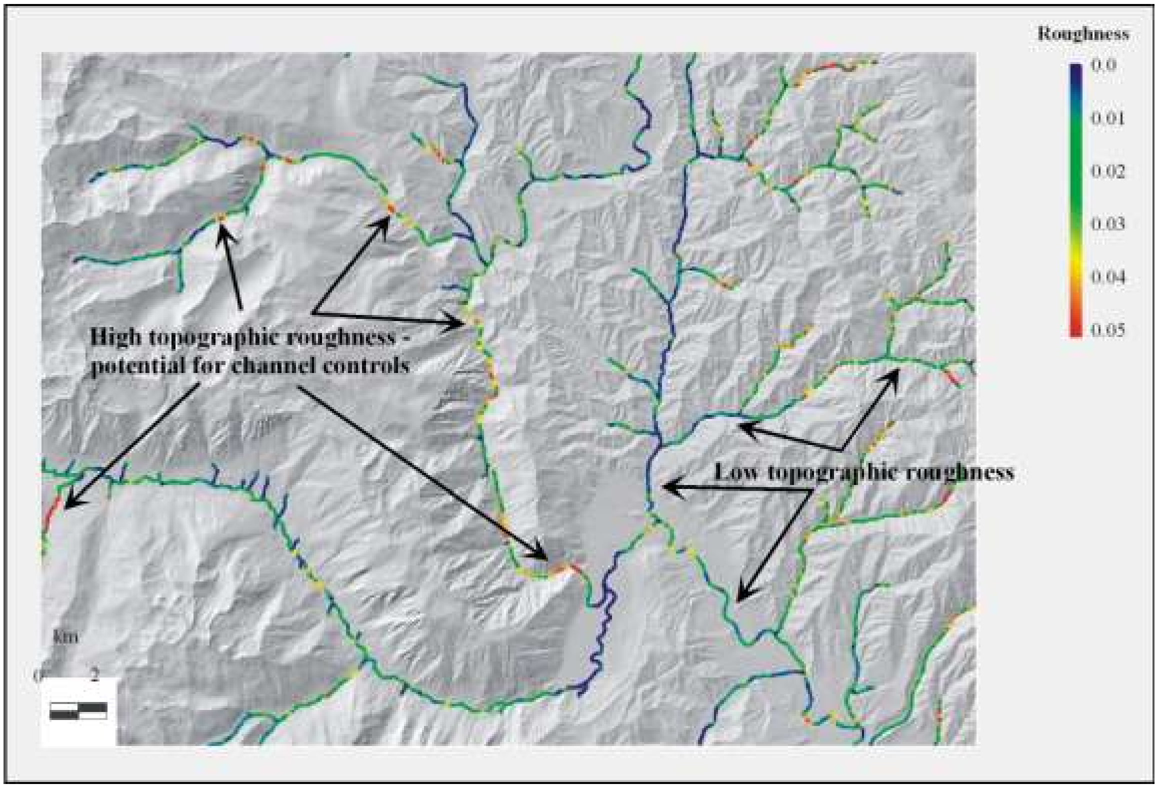


Figure 15. Maps of stream-adjacent topographic roughness indicate where topographic controls on river morphology are likely to occur in watersheds. Such areas may also correspond to valley constrained reaches (e.g., Figures 30 – 32). The CDF of roughness indices comprises a queryable database within TRIAD from which multiple basins can be sorted and ranked.

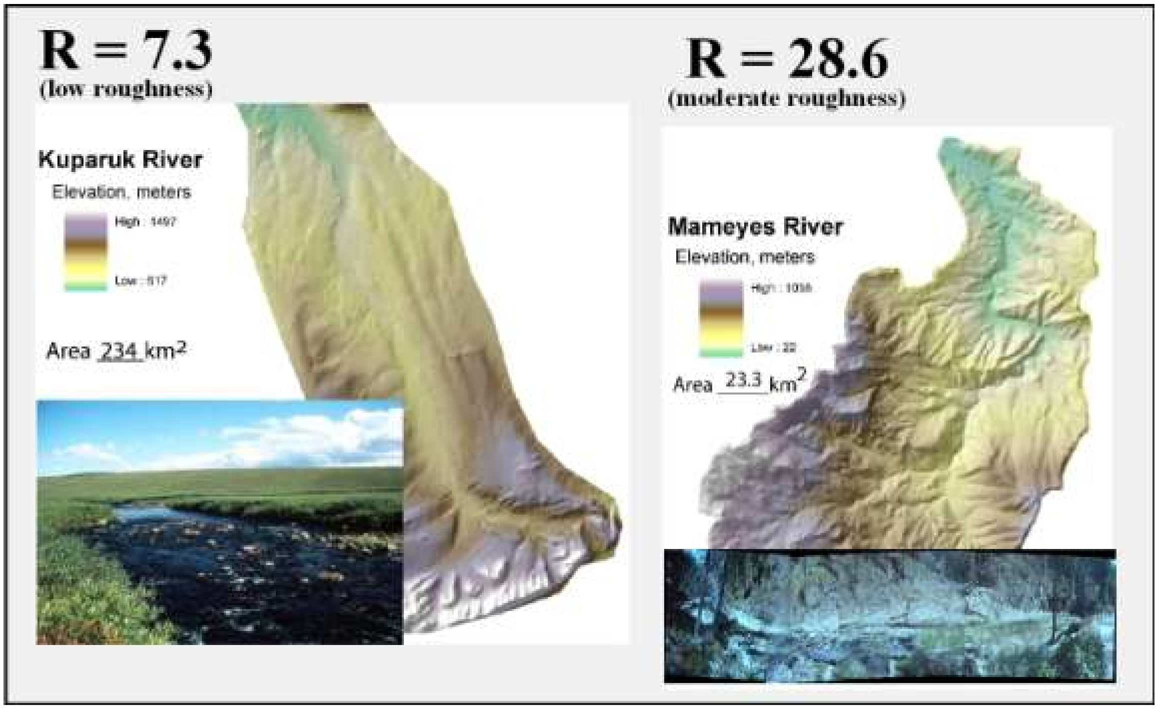


Figure 16. An index of topographic roughness for entire watersheds provides an indication of the overall degree of steepness and slope variability, and hence to the types of geomorphic processes that occur and the resultant forms of rivers. For example, the low roughness of the Kuparek River on the Arctic Plain (left panel) corresponds to low relief and low variable terrain where river morphology is dominated by meandering pools and riffles (and thermal melt pools in the tundra). In contrast, the higher roughness terrain of the Mameyes River basin in Puerto Rico (right panel) should be associated with numerous river forcing agents such as landslides, debris flows, earthflows, ridges, and bedrock outcrops, etc. Consequently, the Mameyes River should have a significantly higher degree of morphological heterogeneity compared to the Kuparek River.

impacts from resource management. Surficial deposits in watersheds can also contribute to water quality problems. For example, thick deposits of outwash sand and lucustrine silts created during past glaciations in certain landscapes can provide fine sediment that contributes to suspended loads and turbidity. In addition, mechanically weak rocks create fragile bedload that breaks up in transit, potentially leading to sediment-impoverished channels (Benda and Dunne 1997,b).

TRIAD therefore employs a watershed parameter of geology, specifically lithological type when open source digital databases are available. Rock strength that may be a useful index for water quality concerns is also indexed using the rock hardness classification system of Selby (1985) (Table 3).

3.2 Second Parameter Domain: Basin Shape, Network Configuration, Valley Morphology, and Basin Size

In this section TRIAD addresses the role of basin shape, channel network configuration, valley morphology, and basin size on riverine habitat types, their distributions, and their sensitivity to disturbances. Drainage and tributary confluence density are also included. The potential role of basin shape on the relative proportions of different channel types (i.e., pool riffle versus boulder step pool) is discussed. This section also addresses how basin scale influences the separation between habitat patches ranging from meander pool-riffles to local morphological changes around tributary confluences, and the size of habitat patches.

The following parameters are included in the second domain: 1) basin shape, network configuration, and confluence effects, 2) basin shape and different channel types, 3) valley morphology and the structure of variation in constrained and unconstrained segments, and 4) basin size and the scale of habitat patches.

3.2.1 Basin Shape, Network Configuration, and Tributary Confluence Effects

The influence of tributaries on mainstem streams and rivers are well recognized, although not often quantified. Tributaries can deliver higher inputs of nutrients and invertebrates that have been shown to increase primary and secondary productivity in receiving streams at confluences (Kiffney and Richardson 2001, Wipfli and Gregovich 2002). Fish may use

Table 3. Rock types are classified by their mechanical strength (after Selby 1985).

Description	Strength Class	Examples of Rock Types
Very weak rock: crumbles under sharp blows with hammer pick point, can be cut with a pocket-knife.	5	Chalk, rocksalt, lignite
Weak rock: shallow cuts or scratches may be made with a sharp knife, pick point indents deeply with firm blow.	4	coal, siltstone, schist
Moderately strong rock: knife cannot scape surface, shallow indentation under firm blow from pick point.	3	slate, shale, sandstone, mudstone, ignimbrite
Strong rock: hand held sample breaks with one firm blow from hammer end of geological pick.	2	marble, limestone, dolomite, andesite, granite, gneiss
Very strong rock: requires many blows from geological pick to break intact sample.	1	quartzite, dolerite, gabbro

tributary mouths as thermal refugia (Scaarnecchia and Roper 2000) or as dispersal corridors that support higher species diversity (Osborne and Wiley 1992). Tributaries also alter the hydraulic geometry of receiving streams including width, depth, and bar size and occurrence (Best 1986, 1988, Roy and Woldenberg 1986), and they can alter the particle size distribution either coarsening or fining the channel bed (Rice et al. 2001). Variations in hyporheic exchange also commonly occur at confluences (Baxter and Hauer 2000).

On a somewhat larger morphological scale, topographic knick points in rivers associated with tributary fans and sediment mixing at tributary intersections result in a large variety of morphologic effects at and near confluences including terraces and wide floodplains, channel meanders and braids, changes in bed substrate including boulder deposits and rapids, deeper and wider channels, mid-channel bars, ponds, and log jams (Church 1983, Best 1986, Grant and Swanson 1995, Hogan et al. 1998, Rice et al. 2001, Benda et al. 2003) (Figure 17).

All of these nutrient, thermal, and morphological effects can contribute to habitat heterogeneity and hence tributary confluences can be biological hot spots (Benda et al. 2004,a). Consequently, the pattern of the channel network in terms of spacing and size of tributaries in a watershed should influence the non-uniform distribution of certain types of habitats and habitat heterogeneity linked to confluences (Figure 18). For example, geological or topographic constraints on the formation of tributary basins can lead to clumped distributions of intersecting tributaries and associated confluence-derived heterogeneity (Figure 18). Overall, morphological effects of confluences may tend to be most pronounced in lower-gradient portions of rivers and may decline in steep, narrow valleys where high stream energy quickly erodes fans, or in wide valley floors where fans are isolated from mainstem rivers. In addition, the erosion regime of a watershed, particularly if it is punctuated in time, may influence how tributary confluences affect mainstem channel morphology and this aspect is discussed in greater detail in the fourth domain of climate and disturbance.

The probability of observing confluence-related changes in the morphology of mainstem channels depends on the size of the tributary relative to the mainstem (Benda et al. 2004,a). Logistic regression equations are used in *TRIAD* to predict the probability of confluence effects (Benda et al. 2004,b), a relationship that varies between humid and semi-arid landscapes (Figure 19). High confluence ratios (i.e., tributary drainage area/mainstem drainage area) indicate a high potential for various tributary confluence effects. Network

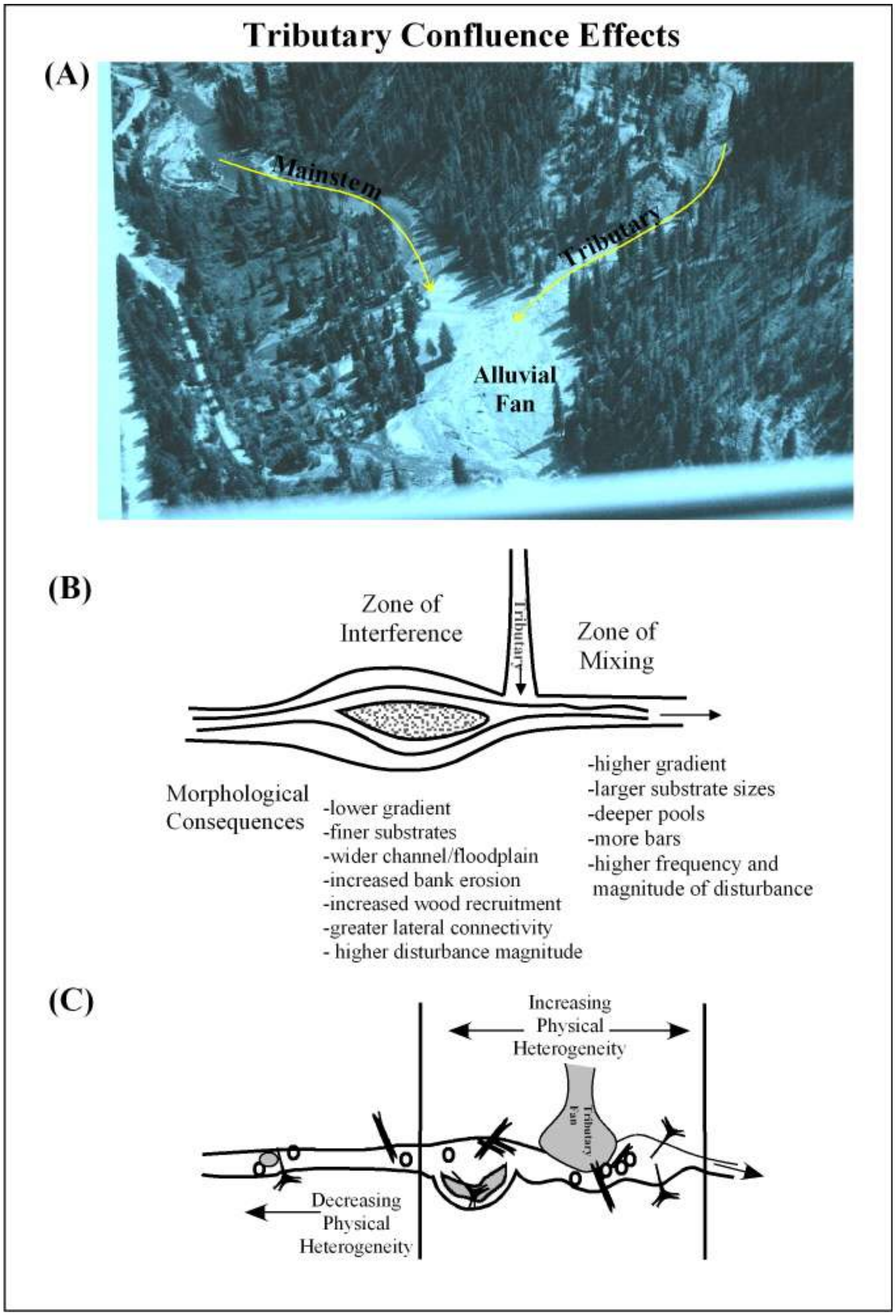


Figure 17. The potential influences of tributaries on receiving channels are numerous and include nutrient, thermal, chemical, hydrological, and morphological effects. Depicted here are potential sediment-related morphological effects that can occur at confluences both upstream (referred to as “interference”) and downstream (referred to as “mixing”). Consequently confluence areas can be zones of higher morphological heterogeneity, although punctuated disturbances cause such effects to wax and wane over time throughout river networks. Post fire erosion and sedimentation creates large fans and confluence effects as shown in the Sawtooth Mountains of Idaho (A).

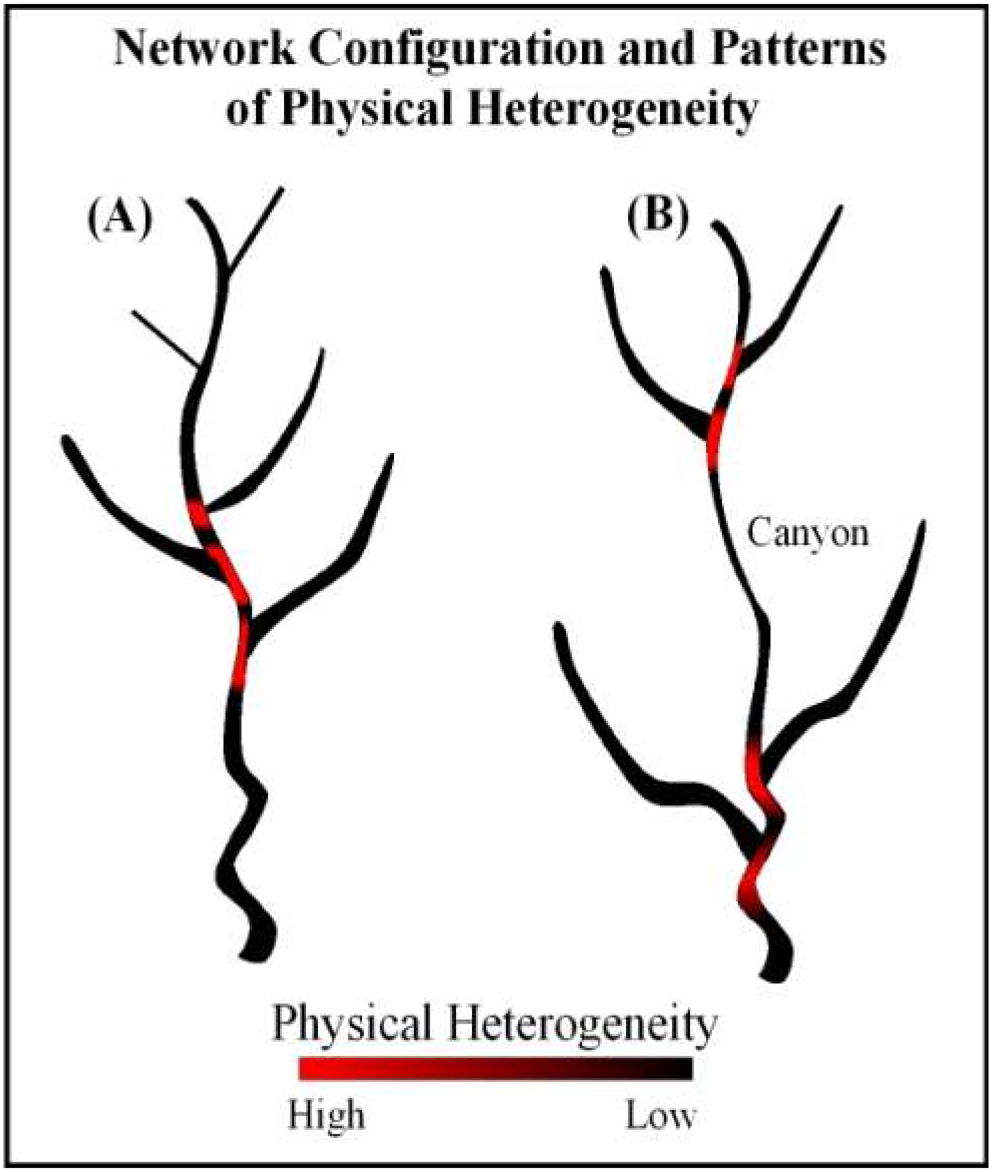


Figure 18. Variation in river network patterns should influence the spatial distribution of certain types of river morphology and habitats associated with tributary confluences. A convergence of many large tributaries should lead to a higher degree of morphological heterogeneity and other confluence effects (A) compared to channel segments devoid of larger tributaries (B).

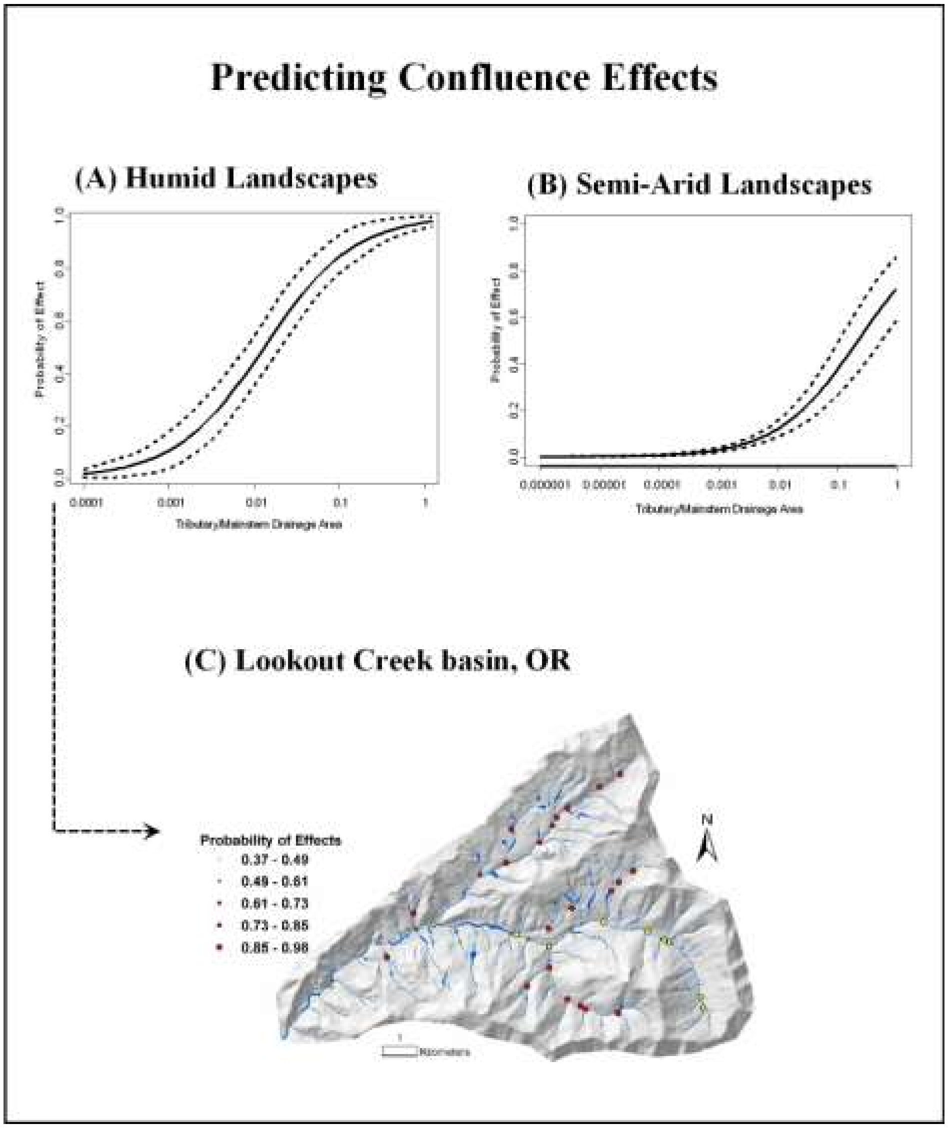


Figure 19. In general, the probability of a tributary impacting the morphology of a mainstem river depends on the size of the tributary relative to the size of the mainstem. Data from 14 studies in western United States and Canada along 730 km of river encompassing seven orders of magnitude in drainage area were used to develop logistic regression equations for semi-arid and humid landscapes (A & B) (Benda et al. 2004,a,b). The model can be used to predict the likelihood of confluence effects (C). Other factors are important such as time since last fan-forming event (storms, fires, floods), the grain size of the transported sediment, and valley width.

The probability of confluence effects for a given tributary – mainstem drainage area ratio is higher in humid environments compared to semi arid. This disparity may reflect differences in disturbance frequency and magnitude. In semi arid environments, disturbances (such as post fire gully erosion) may have an extreme magnitude but may occur relatively infrequently. Consequently, the age distribution of confluence effects may be skewed toward older age classes, creating fewer confluence effects at any point in time in semi arid lands compared to humid environments.

maps display the spatial distribution of tributary confluences predicted to have a high potential of altering channel morphology and creating areas of potentially high biological value (Figure 20). Other factors can strongly influence the extent and magnitude of confluence effects including erosion processes, grain size of transported sediment (by debris flow, flash flood, and runoff floods), and time since last fan-building event. Some of these are included in *TRIAD* parameters and others would need to investigated in the field.

Channel network configuration (i.e., trellis versus dendritic) will strongly influence channel network patterns and the spatial pattern of predicted confluence effects. Network configuration is related to basin shape. For instance, narrow rectilinear-shaped basins that favor trellis networks are predicted to have less opportunity to create geomorphically significant confluences because of the absence of large intersecting tributaries. In contrast, oval- or heart-shaped basins contain dendritic networks and have a greater number of larger intersecting tributaries (Figure 20). Basin shape is used as a watershed parameter in *TRIAD* to describe a basin's overall potential for tributary confluence effects and hence it is used as an index to sort and rank watersheds according to the propensity for confluences to create habitats. Basin shape is defined as mainstem channel length, squared, divided by basin drainage area producing a dimensionless index (U. S. G. S. 1999). A 'mainstem channel' is defined in a basin by the upstream sequence of tributaries that maintains the largest increase in drainage area as each confluence is encountered. Elongate basins with high shape values (4 - 8) generally contain trellis networks and have a low potential for confluence effects (Figure 20). Oval-shaped basins that have lower shape values and generally dendritic networks should create a higher potential for confluence effects (e.g., Figure 20).

Basin shape and network configuration dictate the downstream sequence of geomorphically significant confluences along mainstem rivers that should relate to downstream patterns of confluence effects and these patterns should have ramifications for the types, spatial distribution, and heterogeneity of aquatic habitats (Figure 21). In addition, basin shape and related network configuration should govern the CDFs of confluence probabilities and the effects of symmetrical or asymmetrical locations of mainstem rivers also should influence downstream patterns of riverine environments (Figure 22). For instance, a CDF indicating a relatively high proportion of high probability confluences should theoretically have a greater degree of physical heterogeneity compared to basins with

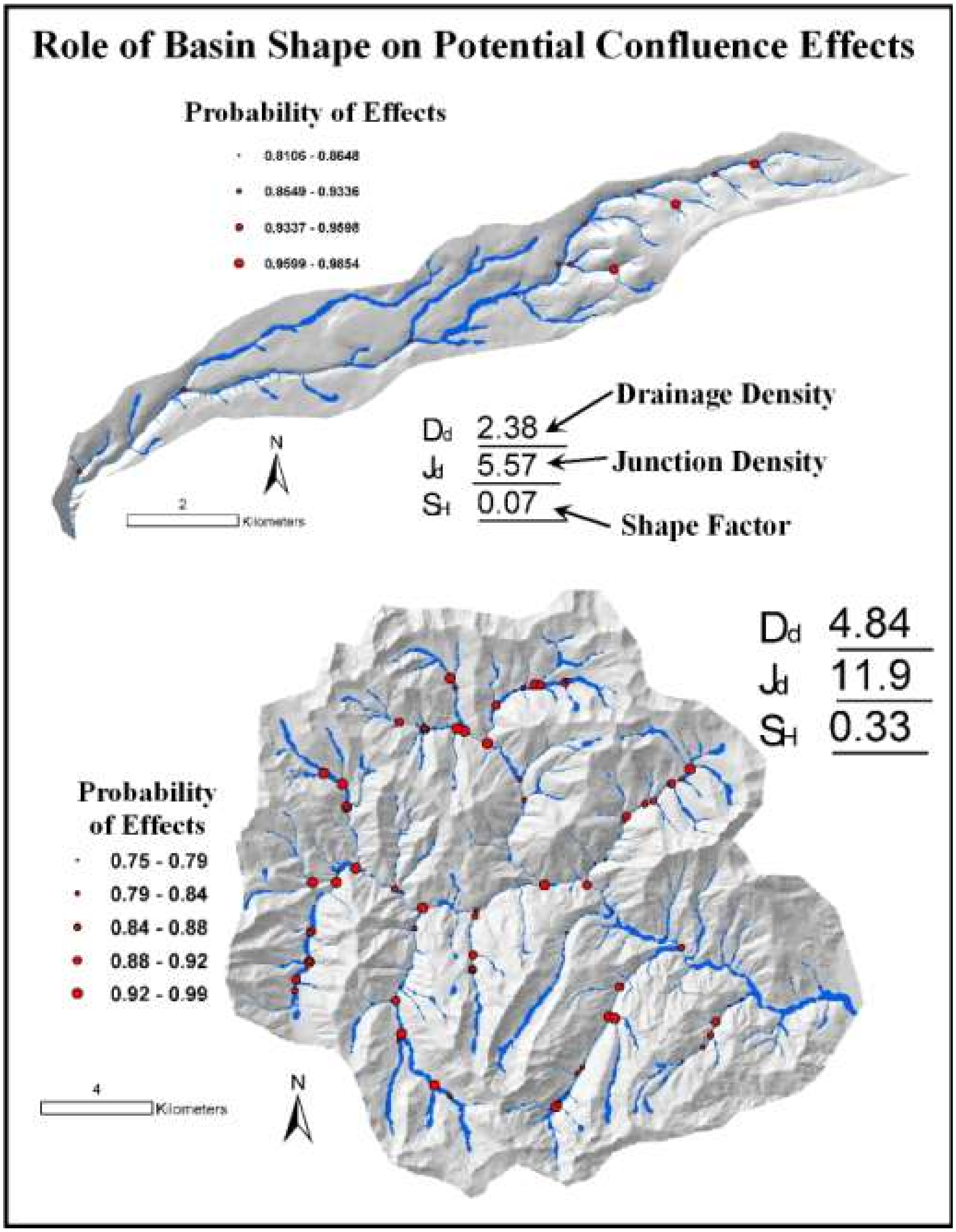


Figure 20. Basin shape (SH in the figure) strongly influences network configuration that in turn controls the spatial pattern of tributary size and their spatial relationship to receiving channels. Consequently, basin shape and network configuration should strongly influence the predicted probability of confluence effects and their spatial patterns in a watershed (Benda et al. 2004a). For example, narrow basins (top) are predicted to have fewer confluence effects compared to dendritic networks (bottom). In addition, drainage density that influences tributary junction density should also influence the number and likelihood of encountering confluence effects in watersheds.

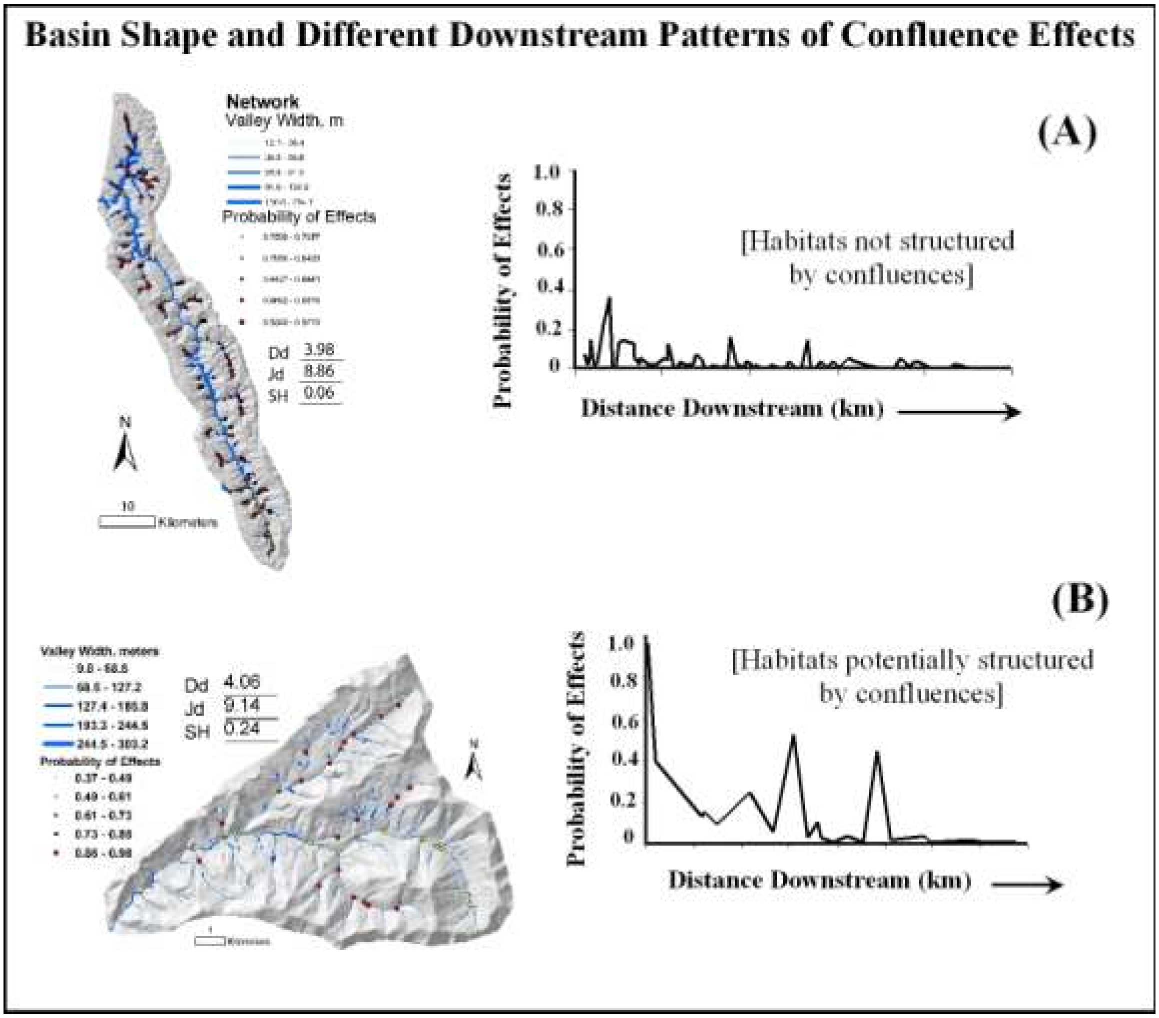


Figure 21. Basin shape and network configuration will affect the downstream pattern of tributary confluence effects and hence certain aspects of riverine habitats in mainstem rivers. (A) Redwood Creek basin in northern California is predicted to have essentially no confluence effects in the lower third of the basin and this accords with field studies (M. Madej, personal communication). However, in the heart-shaped basin of Lookout Creek the potential for confluence effects should be greater.

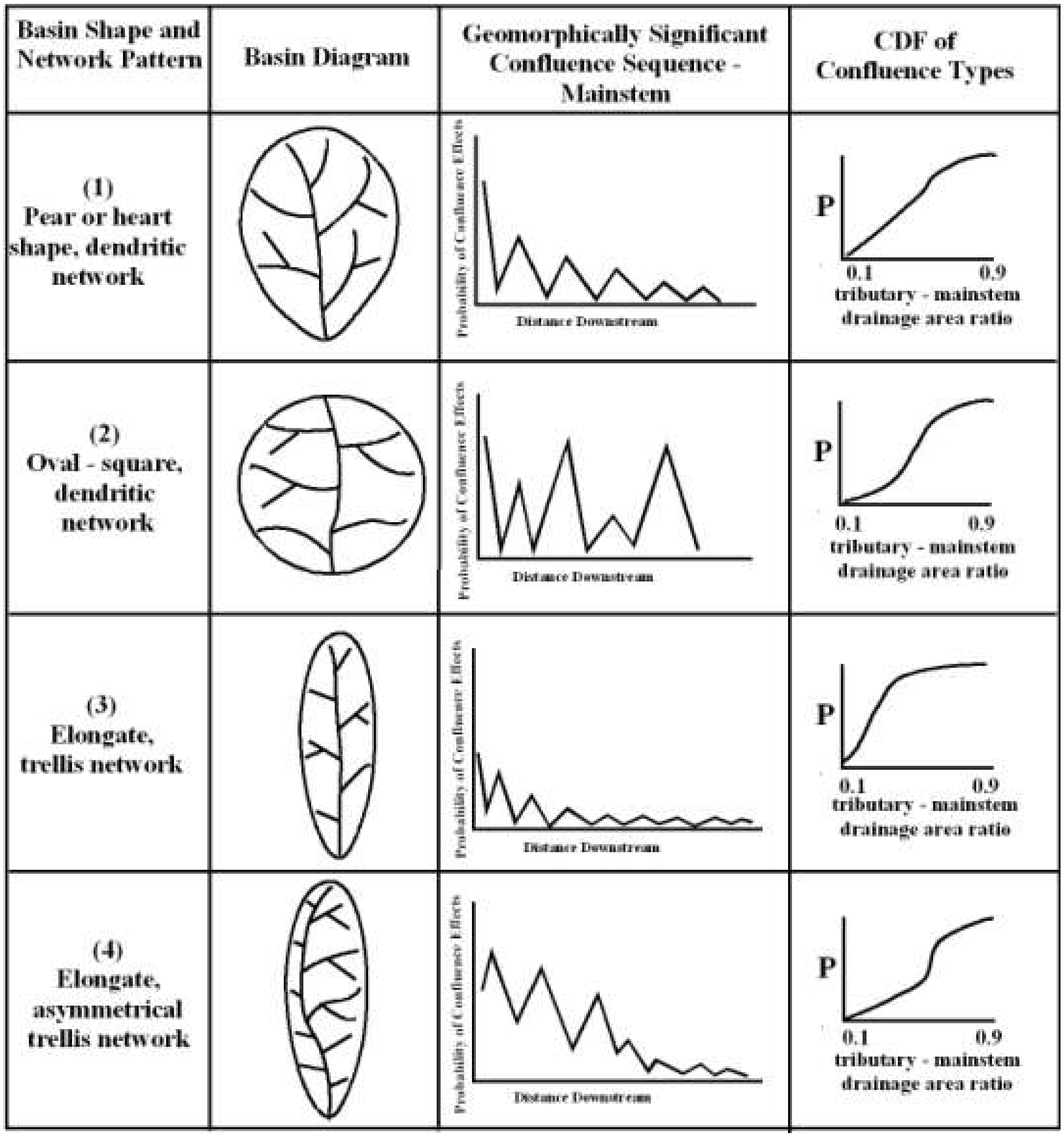


Figure 22. Watersheds are classified by shape and network pattern to help understand the role of confluences in affecting the abundance, types, and spatial distribution of riverine habitats. Variation in network types should also translate to variations in the cumulative distribution functions of confluence probabilities (right hand panel), a network-wide gauge of the role of river networks in habitat formation.

CDFs having a lower proportion of high probability confluences (e.g., Figure 22, panel 2 and 3).

TRIAD also indexes drainage density (channel length/area) and the density of confluences (number of confluences/area). Watersheds with high drainage or junction density potentially should have a higher degree of habitat heterogeneity (e.g., variation in floodplains, side channels, channel gradients, and hyphoreic exchange) compared to basins of lower drainage and confluence densities (Benda et al. 2004,a).

Disturbances such as storms, fires, and floods that trigger erosion and increased sediment supply typically maintain the influences of fans on mainstem morphology. Fans at confluences are formed and rejuvenated during time periods characterized by accelerated sediment supply to rivers (Benda and Dunne 1997, Meyer and Pearce 2003); also see Section 4.0. Consequently, fans expand and contract over time in response to fires, storms, and floods, and the spatial extent of their upstream and downstream zones of influence should vary over time (Benda et al. 2003). For example, during periods of low watershed erosion, alluvial and debris fans become eroded and truncated by floods, whereas during periods of heightened watershed disturbance, fans enlarge and expand in both upstream and downstream directions.

Given this temporal variation, the size of a fan observed at any snapshot in time and their influence on channel morphology should vary with disturbance history. The temporal expansion and contraction of fans is not included in *TRIAD's* analysis of confluence effects because of the absence of historical information, particularly at landscape scales. Hence, the prediction of confluence effects reflects an intrinsic property of networks in a temporally averaged sense. Only a portion of confluences may have morphological effects at any one time. However, the likelihood of encountering confluence effects should vary with location in the watershed. For instance, in upper regions of networks, debris flow or alluvial fans are activated during relatively infrequent (multi-decadal to century) and large magnitude sediment pulses (originating from upstream or within the main channel). The relative rarity of large erosional events higher in networks is caused by infrequency of large storms and fires over small spatial scales (Benda and Dunne 1997b). This should lead to a higher proportion of older and inactive fans. In contrast, confluences lower in the network interact with higher-frequency and lower-magnitude sediment pulses over decades because of the higher cumulative likelihood of basin erosion and floods. Therefore, in addition to having more persistent effects in rivers, junctions of large tributaries located lower in networks should have a greater age and morphological diversity of channels, floodplains, and terraces (also see Section 3.4.6).

3.2.2 Basin Size, Habitat Patch Size, and Density of Habitat Patches

River habitats are non-uniformly distributed over a range of spatial scales and they include gravel bars, log jams, riffles, pools, side channels, and terraces (e.g., Figure 2). The distance between certain types of habitat patches (and hence their spatial density) generally increases downstream (Figure 23). For instance, the spacing between steps (or step pools) in channels having boulder-step pool morphology is inversely correlated with channel gradient and ranges from 14 m at slopes of approximately 0.05 to between 2 and 4 m at slopes of 0.15 (Grant et al. 1990). Hence, the scale of variation of boulder steps and their associated pools is influenced by river size, although the dependency of channel slope on particle size complicates the relationship. Because boulder step pools are generally confined to upper and steeper portions of mountain drainage basins, the scaling property of that morphology may be less significant compared to the others that may occur throughout a river network.

It is well known that meander wavelength (the distance separating two consecutive bends) varies with channel width, or its surrogate discharge or drainage area (Leopold et al. 1964). In general, meander wavelength is equivalent to 10 – 14 channel widths (Langbein and Leopold 1968) and since discharge scales with channel width, meander wavelength also varies as $Q^{0.5}$ (Knighton 1998). Channel meanders also form in bedrock channels given sufficient time for bedrock erosion. Because meander wavelength scales with basin size, the density or separation distance between the different habitat patches (i.e., pools and riffles) increases non-linearly downstream with increasing river size (Figure 23). For instance, meander wavelength (and the distance separating major pools and riffles) can vary from ten meters in channels of several meters wide to greater than 10 km in kilometer-wide channels (Leopold et al. 1964). Moreover, the length of habitat types, such as pools that form at channel meanders (i.e., related to the size of the bend) also increase correspondingly with meander wavelength.

Another feature that scales with river size is log jams. Because mobility of logs increase with river size (Lienkaemper and Swanson 1987), the spacing of log jams increases downstream in non braided channels, ranging from tens of meters in small streams to hundreds of meters in larger ones (Martin and Benda 2000). In addition, since the supply of wood to streams and rivers depends on length of streamside forests (i.e., between jams), the size of log jams (i.e., number of pieces and likely their length) should also increase downstream in accordance with increasing jam spacing. The pattern of larger wood jams separated by increasing distances downstream have been observed in the field (Bilby and Ward 1989, Martin and Benda 2001) and predicted in model simulations (Benda and Sias 2003), although the pattern breaks down in very large rivers (where all wood is transportable) or in braided river systems that may have limited capacity to transport logs. In larger rivers (channels significantly wider than tree height) where all wood becomes mobile, clumps of woody debris form creating mid channel bars and islands with subsequent flow diversion creating anabranches and multiple channels (Abbe and Montgomery 1996).

Since larger tributaries are required to create confluence effects in larger rivers as previously described, there should be an increasing separation between geomorphically significant confluences downstream in many networks (Benda et al. 2004a,b). Field data provide evidence for this relationship (Figure 24, A). For instance, at drainage areas less than 10 km^2 the distance separating geomorphically significant tributaries is on average several hundred meters. In larger drainage areas between 100 and 380,000 km^2, the distance separating geomorphically significant tributaries ranges between 2 and 60 km (Figure 24, A). A similar pattern might hold for the number and length of alternating canyon and floodplain segments (Figure 23 A). However, more analysis on this pattern is warranted considering the paucity of information on spatial patterns of floodplains and canyon segments across a population of watersheds.

The data in Figure 23 A can be used to construct functional relationships between drainage area (or channel size) and the separation distance of habitat patches associated with the various forcing elements (i.e., canyons, floodplain segments, log jams, confluences, etc.). This could provide an indication of the change in density of distinct patches as basin size increases or as channel network configuration changes. Such information might prove useful when comparing habitat properties across watersheds for restoration or resource management planning. For example, information on habitat density could be used to prioritize culvert resizing for increasing access to certain habitats. However, predictions about generalized patterns of habitat density should be conditioned by other information (in TRIAD) such as

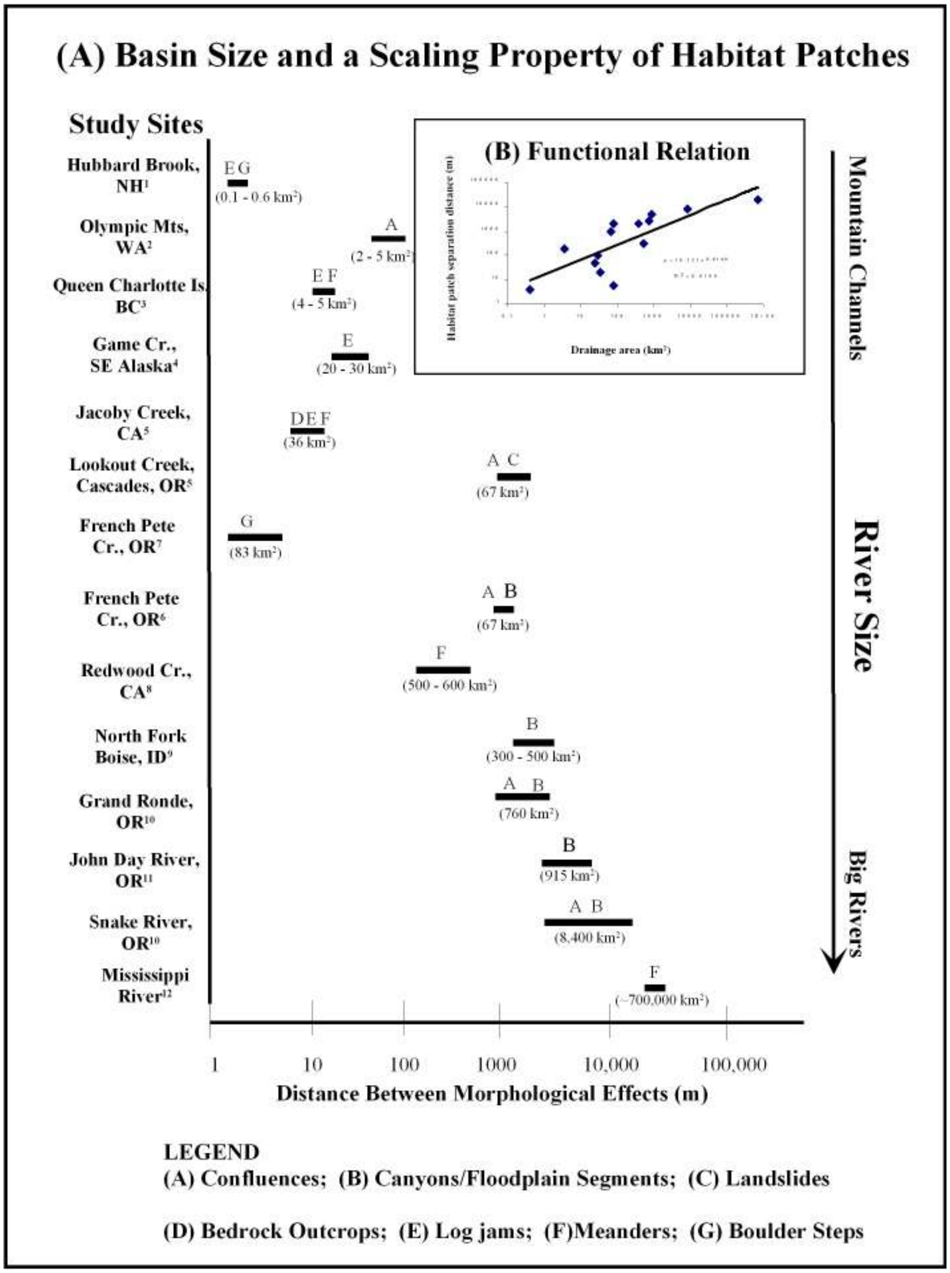


Figure 23 (A). The size of drainage basin will affect the spatial patterns of habitat formation by a variety of processes ranging from boulder step-pools in high mountain channels, to channel meanders, and to confluence effects. Data shown here from 14 studies spanning six-orders of magnitude in drainage area indicate how habitat patches created by various processes increase their separation distance downstream (and decrease their density). Habitat patches in upper networks might only be separated by several tens of meters while habitats in the larger rivers can be separated by tens of kilometers. (B) The functional relationship between separation distance and drainage area is used in TRIAD to predict the variation in that habitat attribute across different watersheds; different basin sizes and network configurations will produce different patterns.

the occurrence and patterns of habitat forming processes responsible for confluence effects, canyon and floodplain segments, and log jams, etc.

In addition to separation distance, the size of habitat patches should also increase downstream. Field measurements indicate that the zone of morphological influence of a tributary on a receiving channel, for example, ranges from tens of meters at drainage areas of less than 10 km^2 to thousands of meters at drainage areas greater than 1000 km^2 (Figure 24, B). This is due to a downstream decrease in channel slope that causes any knick-point, such as a tributary fan impinging on a river (e.g., Figure 17, A), to influence a longer length of channel. Because of the availability of data, the potential tributary zone of influence (in receiving channels) is included in *TRIAD*. First, for each tributary, the probability of confluence effects is estimated using the logistic regression described previously (e.g., Figure 19). The tributary zone of influence in the mainstem channel is calculated as a power function of drainage area, using the data in Figure 24, B. The confluence probability is then applied to all mainstem channel pixels within the predicted zone. Closely spaced tributaries can have overlapping patches. Consequently, the spatial pattern of channels potentially exposed to confluence effects should vary significantly across watersheds (Figure 25). Undoubtedly habitat patch sizes associated with other watershed features (meanders, log jams, etc.) should also increase downstream but this aspect is not presently included because of the lack of information. *TRIAD* also calculates a CDF of the proportion of confluence-influenced channels in watersheds allowing cross-basin comparisons of potential confluence effects.

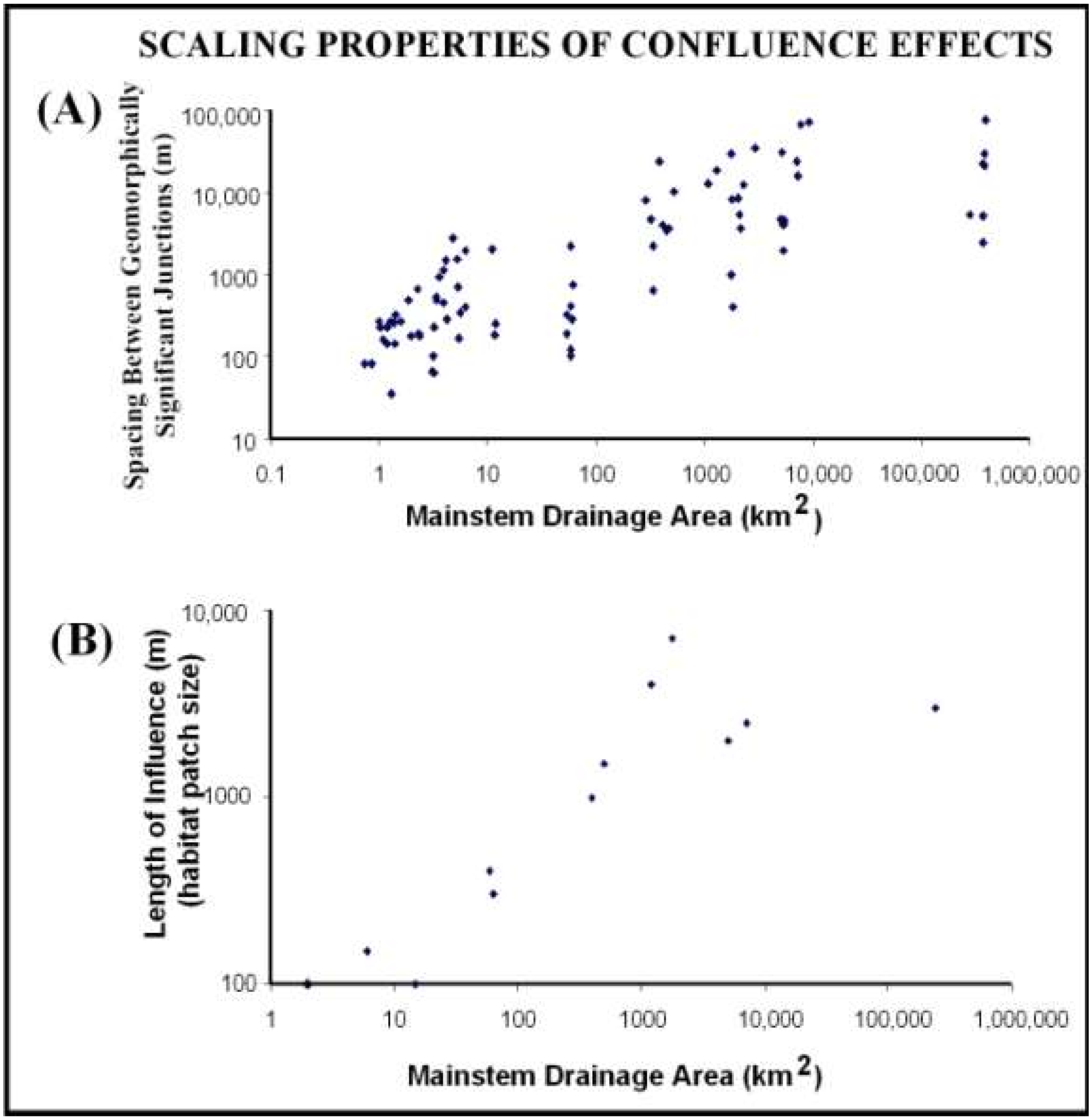


Figure 24. (A) The effect of basin size on the distance between tributary confluence effects is evident from field data obtained from 14 different studies across humid and semi-arid landscapes (Benda et al. 2004a). In upper networks, geomorphically significant confluences are separated by hundreds of meters but in larger rivers they are separated by tens of kilometers. (B) Because channel slope decreases downstream, the size (length) of morphological changes associated with tributary confluences increases downstream, from 100 m in upper networks to kilometer-long patches at basin sizes of 10,000 km^2.

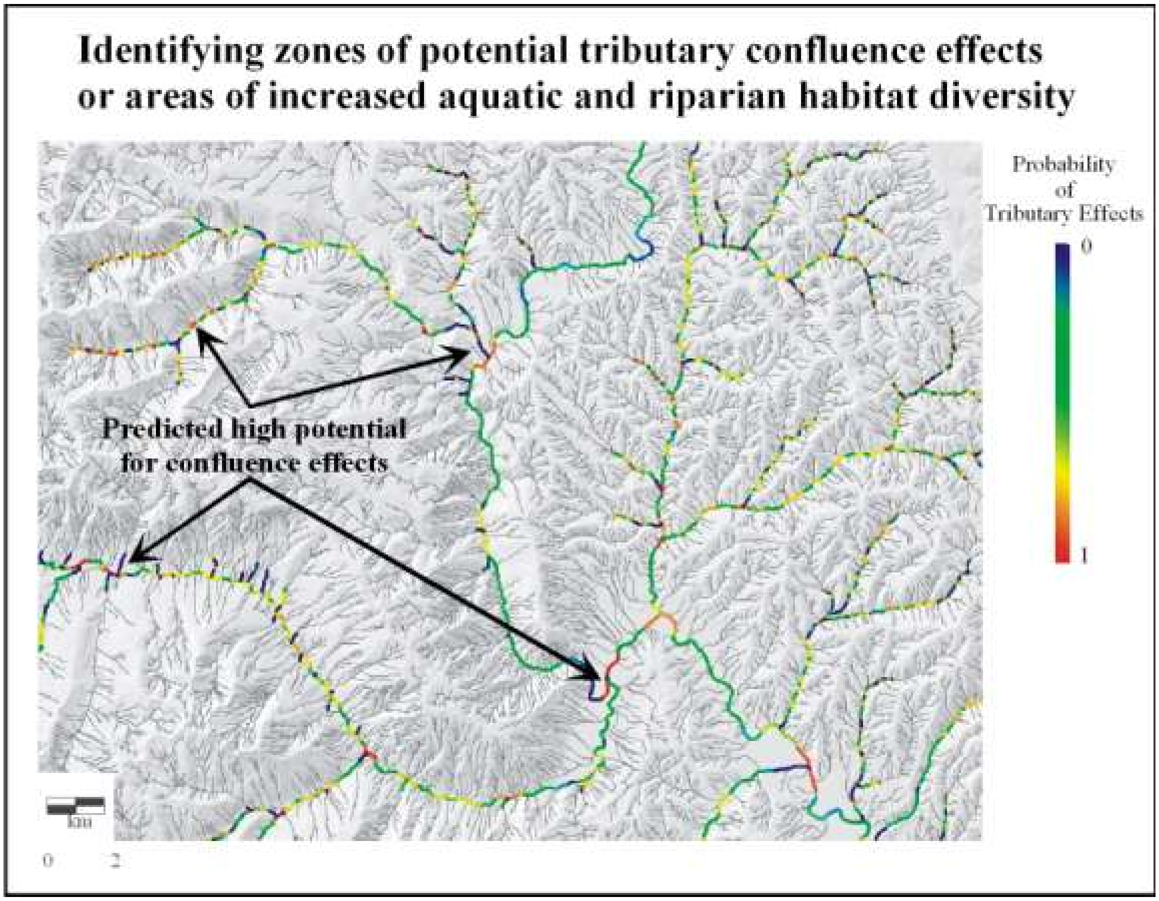


Figure 25. Based on the relationships shown in Figures 19 through 24, models can map out the location and lengths of potential zones of confluence effects in river systems. Such information could be used to anticipate where in river networks certain types of habitats might be found. Cumulative distributions of length-scaled probability of tributary effects are used within TRIAD's queryable database to search, sort, rank, and compare watersheds across landscapes.

3.2.3 Basin Shape and Proportion of Different Channel Types

In many mountain environments channel morphology ranges from boulder cascades to lower gradient, alternating pools and riffles. Variations in channel type correspond to variations in habitat types (Bisson et al. 1982). For example, coho salmon prefer lower gradient, pool and riffle systems, while steelhead trout prefer steeper, riffle and cascade streams (Reeves 1998). Pool-riffle systems that provide good habitat for coho salmon are commonly in the range of 1 to 2% in contrast with steelhead streams that can range from perhaps 4 to 8%. The relative proportions of different channel types within the fish-bearing range of channels in a watershed can have important consequences for watershed management. For instance, watersheds with a higher proportion of lower-gradient channels may be managed differently compared to systems that have a higher proportion of steeper habitats.

The role of basin shape on the spatial pattern of tributary confluence effects was described in 3.2.1. Basin shape may also influence the relative proportions of lower-gradient versus higher-gradient channels in a watershed. For example, with all other things being approximately equal (i.e., lithology, climate, relief, basin size, etc.), rectilinear-shaped watersheds may favor a higher proportion of lower-gradient habitats in contrast to oval-shaped basins that may favor a higher proportion of higher-gradient habitats (Figure 26). This may occur because of the differences in the distribution of stream sizes between the two basin shapes. In general, channel slope decreases with increasing basin size or discharge (Leopold et al. 1964). In rectilinear-shaped basins there are many small streams with small drainage areas (and hence higher gradient) and only a single large trunk stream with larger drainage areas that should have relatively lower gradients. In contrast, the oval-shaped basin has more intermediate-sized streams and basins (and hence intermediate gradients) and consequently should have a relatively lower proportion of its fish-bearing channel system in lower gradient environments.

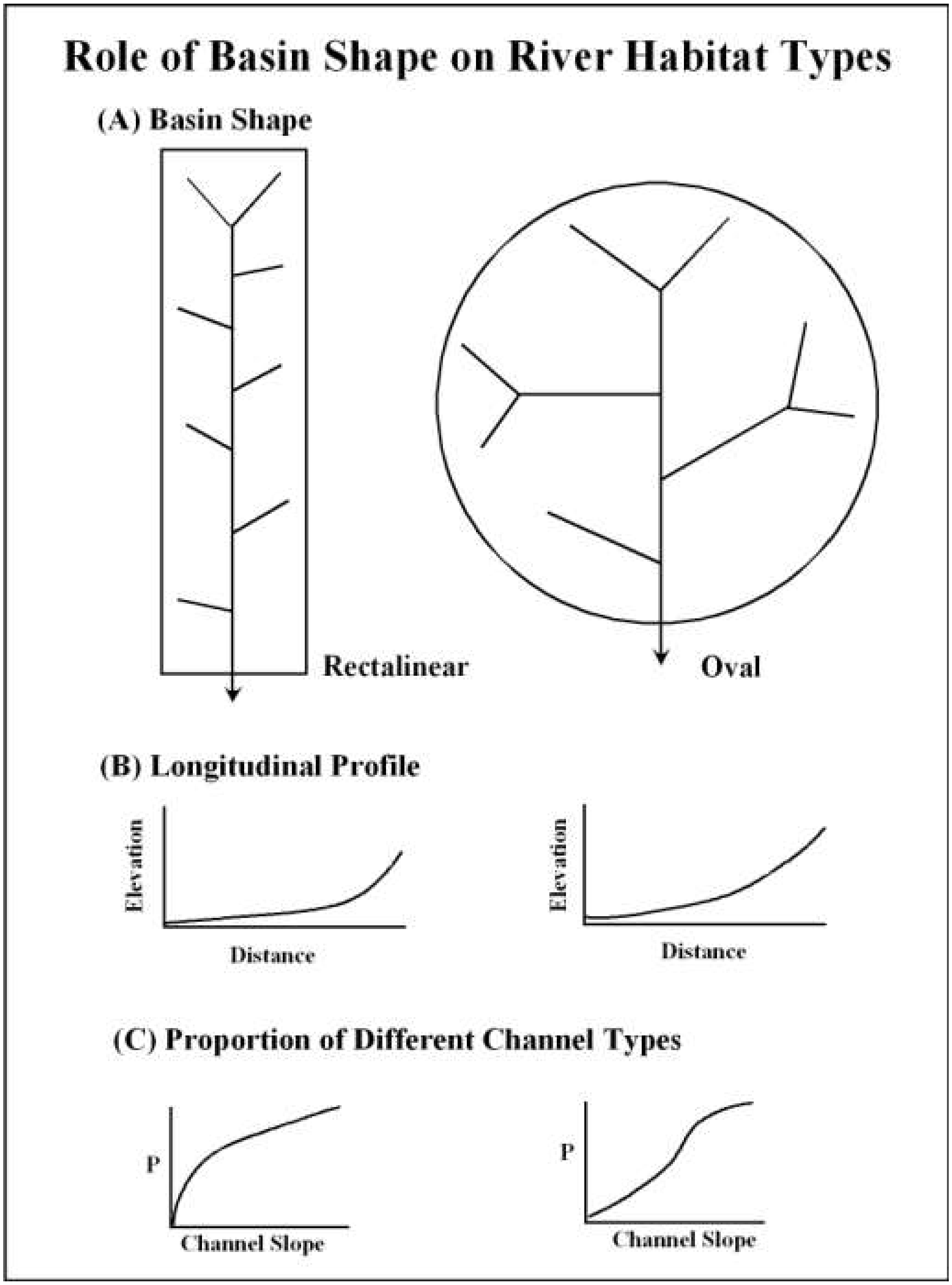


Figure 26. The role of basin shape on many attributes of riverine processes remains unexplored. One possible consequence of basin shape is its effect on the distribution of channels of different gradients and hence different types. Narrow, rectilinear-shaped basins could theoretically produce a higher proportion of low gradient channels compared to oval shape basins containing dendritic networks, all other things being approximately equal. This hypothesis awaits evaluation with large datasets.

A preliminary example of the potential effect of basin shape on proportion of low gradient habitats is shown for HUC-6th watersheds in eastern Washington. The data show considerable scatter indicating the multifarious controls that govern long profiles of river or the distribution of profiles in a network, including lithology, structure, glaciation, history of erosion, and network configuration, etc. (Figure 27). As mentioned above, the pattern should be most evident in cross-basin comparisons where "everything else is equal". It is unlikely to find a suitable population of watersheds that have similar physiography where all the things that might control river profiles are equal. Nevertheless and despite the scatter, the data appear to show a rising envelope of an effect where increasing shape factor (indicating rectilinear basins) is related to increasing proportion of low gradient (< 2%) channels. Undoubtedly, more study is needed to elucidate the effect of basin shape on various riverine attributes, including the proportion of different channel gradients.

3.2.4 Valley Morphology and the Structure of Variation in Constrained and Unconstrained Segments

Longitudinal variation in valley widths from constrained (canyons) to unconstrained (wide floodplains) segment affects the spatial distribution of certain types of riverine habitats (Frissel et al. 1986, Grant and Swanson 1995, Bisson and Montgomery 1996, McDowell et al. 2001, Baxter 2001) and contributes to habitat heterogeneity. Canyons are often characterized by rapids and bedrock influenced morphology resulting in channels being less sensitive to changes in discharge or fluctuating sediment supply. In contrast, unconstrained floodplain segments store greater volumes of sediment and wood, contain a greater diversity of low-gradient habitats, and are more sensitive to disturbances. Typically, wide valley floors promote formation of wider channels and floodplains (Grant and Swanson 1995, Benda et al. 2003b), higher sinuosity (McDowell 2001), deeper pools (McDowell 2001), greater side channels (Baxter 2001), increased gravel substrate (Perkins 2000), and valley-paralleling side channels. In addition, the transition from floodplain to canyon segments is often reflected in increased hyphoreic exchange (Edwards 1998, Baxter and Hauer 2000). Constrained to unconstrained segments lead to hyporheic down-welling while unconstrained to constrained promote hyporheic upwelling. Discontinuous floodplain segments along a river valley have been referred to as a "string of pearls" by some riverine ecologists (Ward et al. 2002) (Figure 28).

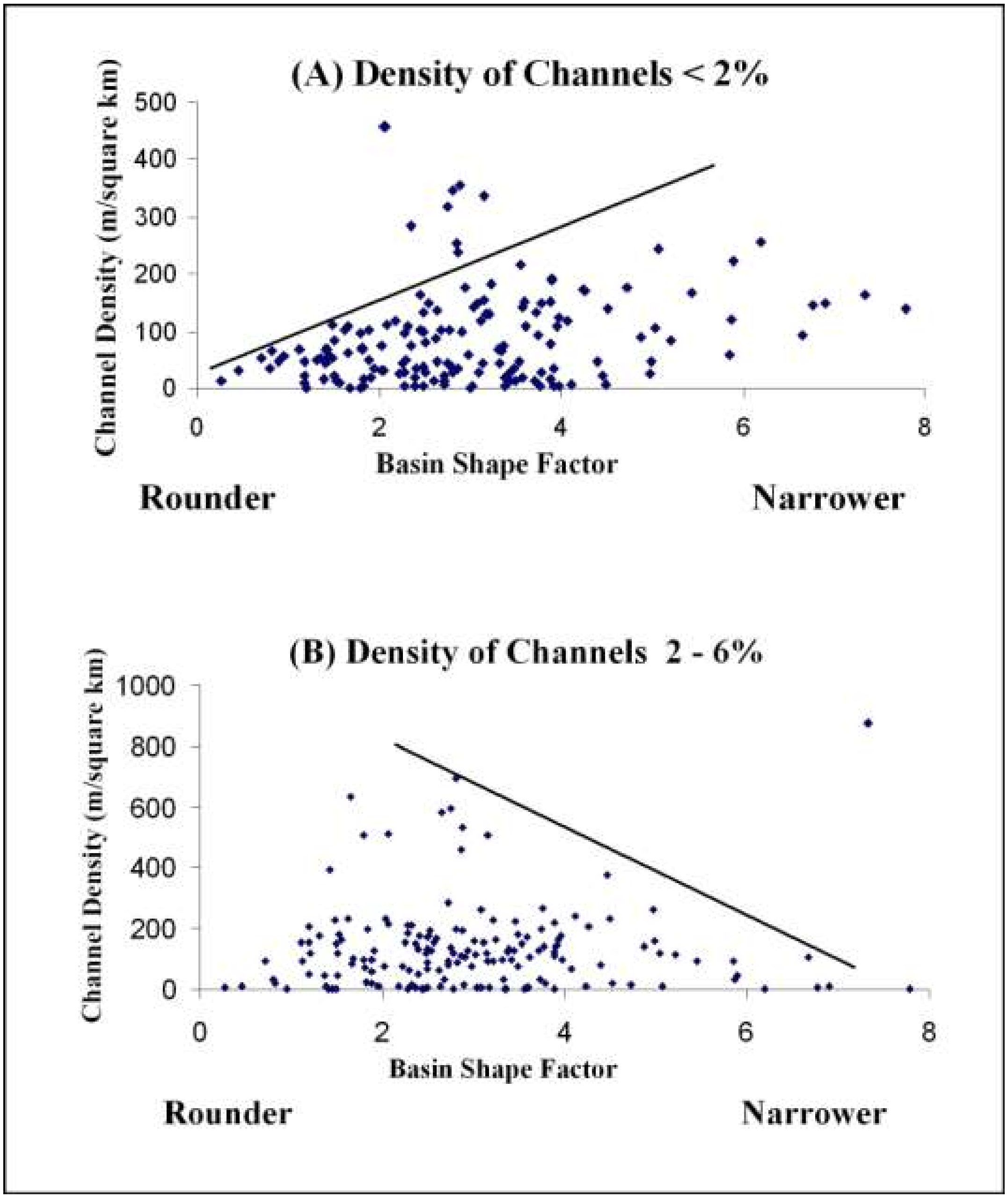


Figure 27. Data obtained from 174 6th-HUC watersheds in eastern Washington are used to make preliminary evaluations of the effect of basin shape on proportion of low-gradient habitats in watersheds. No attempt to sort or classify watersheds into similar groups was made. The data shows considerable scatter probably reflecting the multiple and often unknown controls (in this dataset) on river network profiles. Nevertheless, the data appear to indicate an envelope of an effect whereby the basins with the highest proportion of low-gradient habitats tend to be narrower (A). Additional analysis is needed to further test this hypothesis (e.g., Figure 26).

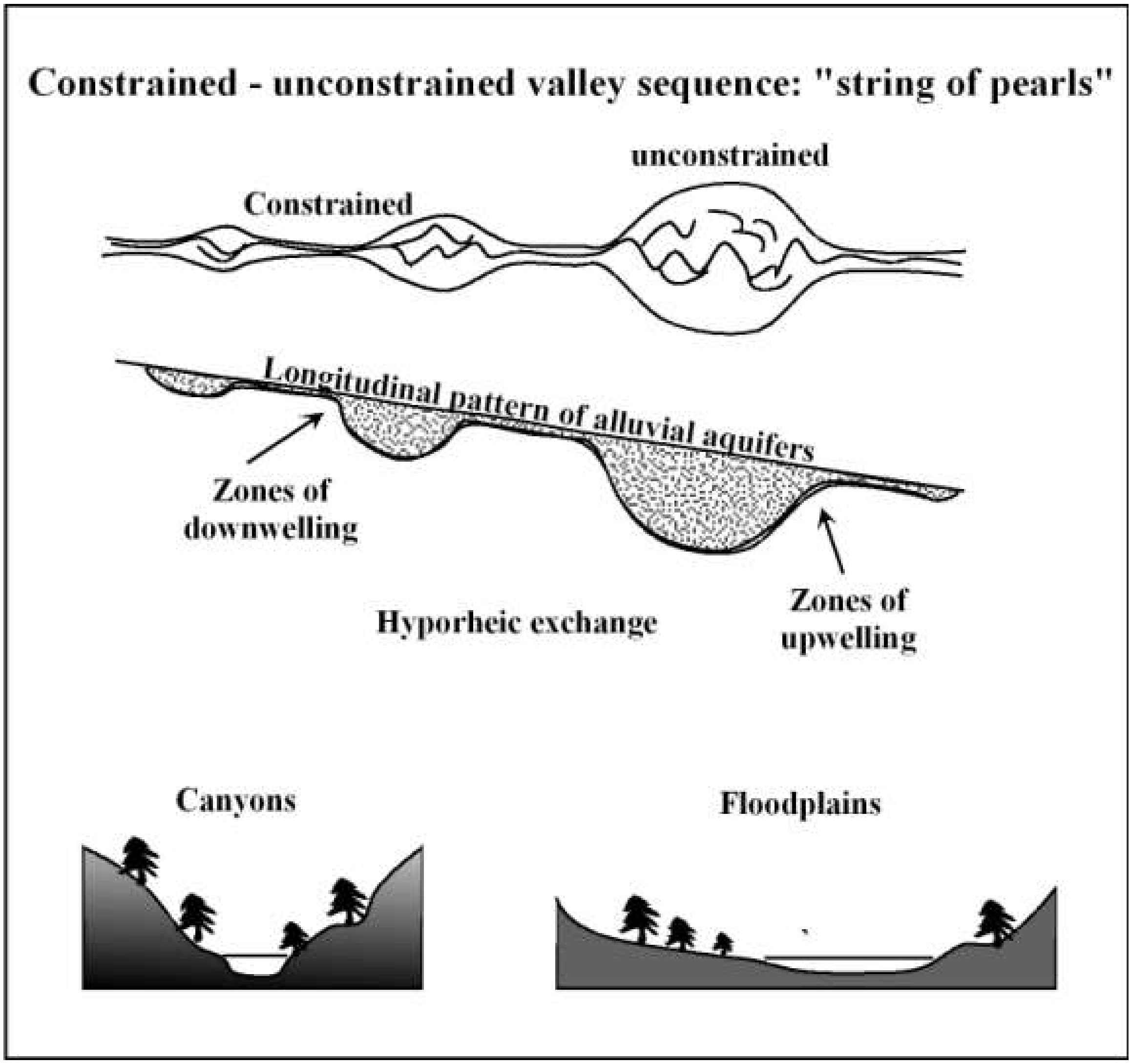


Figure 28. The alternating pattern of constrained valleys (canyons) and unconstrained segments (floodplains) are important in controlling the types, abundance, and spatial distribution of aquatic and riparian habitats within watersheds. Unconstrained floodplain segments generally offer higher quality and more diverse habitats compared to canyons. In addition, transitions between constrained to unconstrained segments favor hyporheic down-welling while transitions between unconstrained to constrained segments favor zones of hyporheic up-welling. Some ecologists refer to the discontinuous pattern of floodplain segments in rivers as "string of pearls" (Ward et al. 2002). Figure adapted from Ward et al. 2002.

TRIAD calculates valley width using DEMs at some defined distance above an estimated bankfull channel depth and is displayed on a map for all channels of 3rd and greater order (Figure 29). However, it is the relative difference between valley width and channel width commonly referred to as ‘channel confinement’ that gauges whether a channel has a floodplain with which to interact with or whether there is a lack of floodplain and the channel is confined. The DEM-estimated valley width is used to characterize valley controls on channel attributes at two scales. At the channel-pixel (reach) scale, *TRIAD* records valley confinement in terms of the valley-width index (VWI) – the ratio of valley floor to channel width (Figure 30). Relationships at this scale push the extent of what can be resolved with currently available 10-m DEMs, but comparison with field observations indicate that meaningful inferences about channel confinement can be made (Coastal Landscape Analysis and Modeling Study [CLAMS], unpublished data). Channel width is based on regression models using field-measured channel widths, DEM-estimated drainage area, and mean annual precipitation (discussed later in Domain #3).

Variations in valley width also affect channel attributes over larger, valley-segment scales. VWI is again used to scale valley width to channel size. Unconstrained valley segments are those through which the VWI value is predominately greater than a specified value; constrained segments are those through which the VWI value is predominately less. Currently, “predominately” is set to 80% by length over distances spanning at least 20 channel widths. Five segment types are delineated: 1) unconstrained, 2) constrained, 3) transitional: unconstrained to constrained), 4) transitional: constrained to unconstrained, and 5) mixed or undetermined. Each reach is classified into one of these five types. Each tributary junction is also classified in terms of the mainstem valley type since the size of the valley likely affects the morphological changes that can occur at confluences. These classifications can be used to calculate several basin attributes: 1) length of channel in each valley type, 2) number of valley segments of each type, 3) number (or density) of tributary junctions in each type (this can be normalized by the probability for tributary effects), and 4) mean and distribution of segment lengths (this can be normalized by channel width to provide comparison across different basin scales). An example of classifying valley confinement is shown in Figure 31; see also Table 2(A,B).

TRIAD also analyzes the structure of variability in valley widths across the 3rd and higher order portion of the network using CDFs (Figure 32). This information can be used to

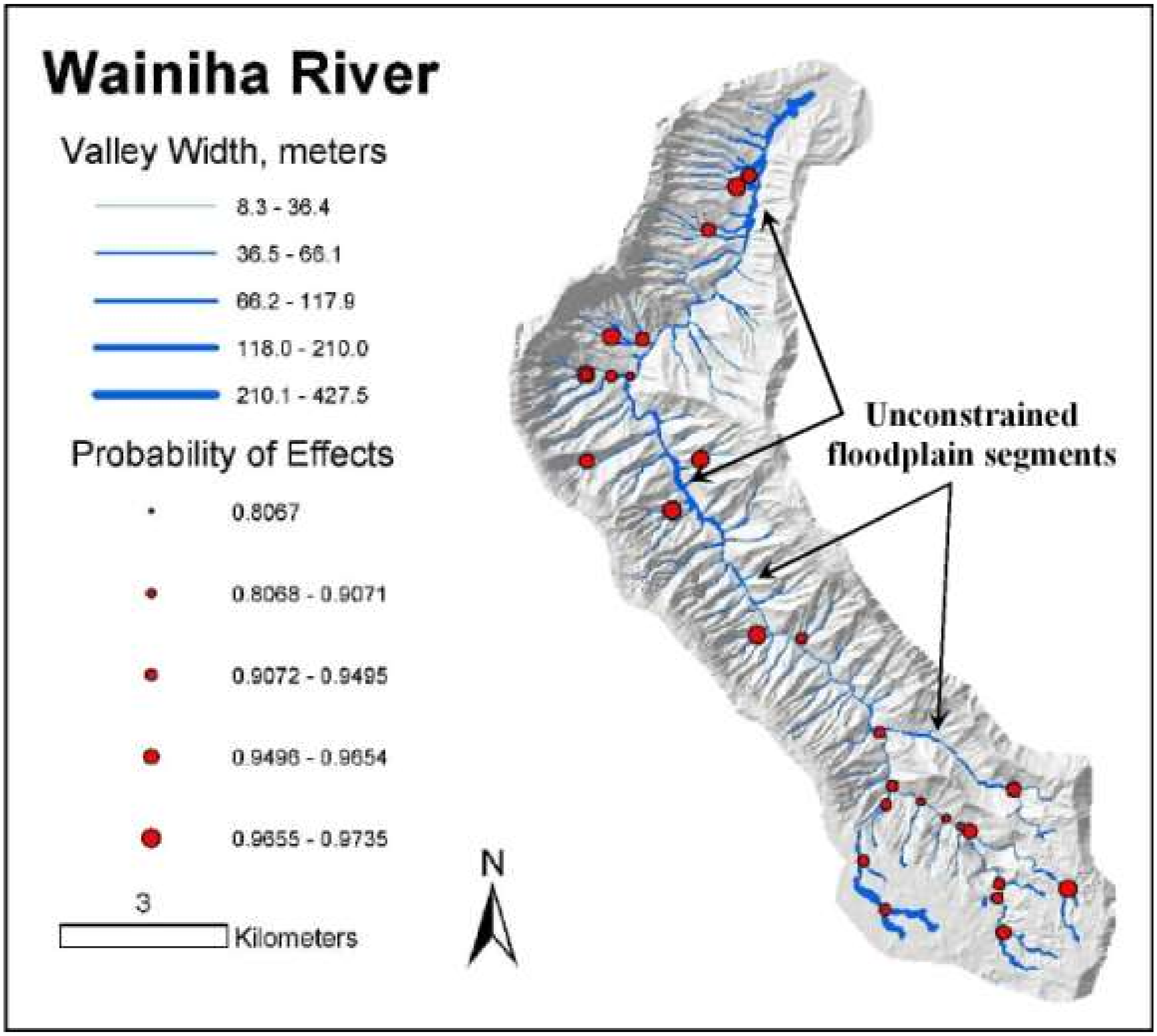


Figure 29. Models can be used to map valley widths across entire drainage basins and hence can be used to indicate the amounts and locations of canyon and floodplain segments. These maps, in addition to predictions of geomorphically significant confluences, can be used to identify areas of the potentially best habitats. Because of the resolution of 10-m digital elevation data, the relative variation in valley widths is more accurate than the absolute measures.

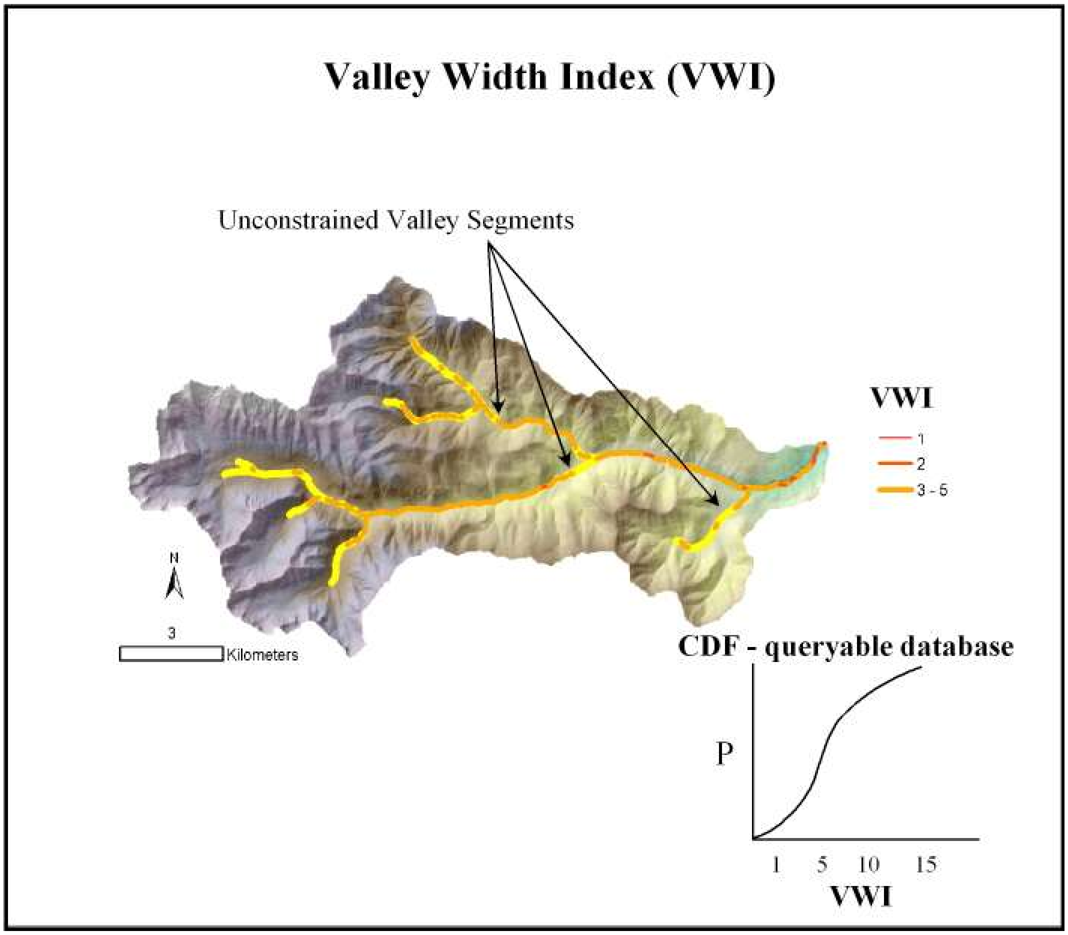


Figure 30. The confinement to a channel imposed by adjacent hillslopes dictates the ability of channels to meander, create floodplains, and anastomose, etc. Hence the relationship between the widths of the valley compared to the width of the channel provides a measure of "confinement", e.g., the valley width index (VWI) calculated by valley width divided by channel width. Information on both channel and valley width is needed, and maps and CDFs can be created from which to assess individual basins or to make cross-basin comparisons.

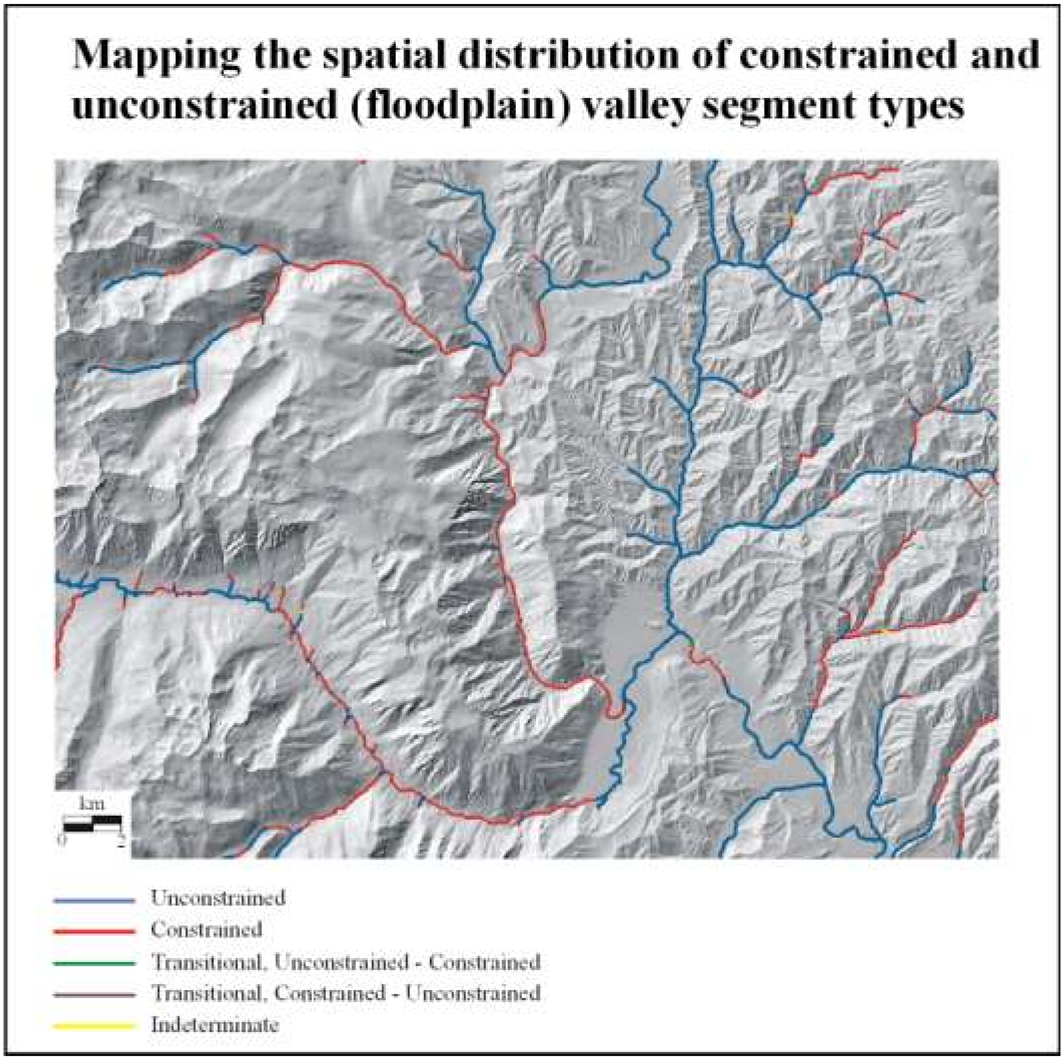


Figure 31. Models can be used to create ecologically relevant categories of valley segment types, including 1) unconstrained, 2) constrained, 3) transitional - unconstrained to constrained, and 4) transitional - constrained to unconstrained.

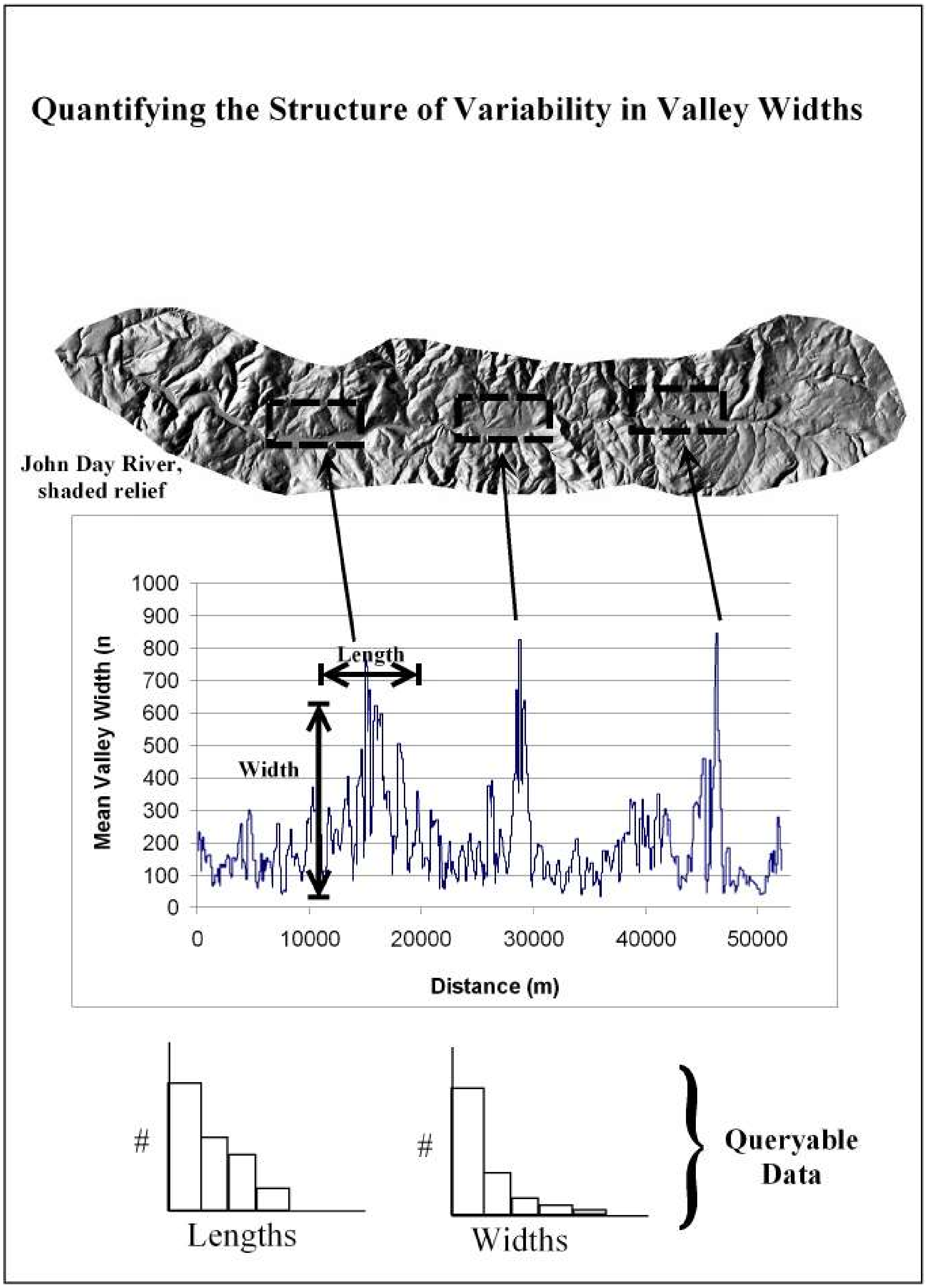


Figure 32. In addition to information on the location and number of constrained and unconstrained valley segments within a watershed, the structure of variation in valley widths can provide important information on differentiating one watershed from another in terms of floodplain habitats. Such information contained in histograms or CDFs would provide the ability to query the database for cross-basin comparisons. The example shown above is from the John Day River where unconstrained valley segments mapped by McDowell (2001) have been detected using 10-m DEMs.

document the number of floodplain "pearls" of varying length and relative width in a watershed. CDFs of valley segment types and physical characteristics contained in a queryable database can be used to sort and rank watersheds according to their number of floodplain valley segments of various sizes and to the overall heterogeneity in valley floor morphology.

3.3 Third Parameter Domain: Channel Geometry, Habitat Types, Wood Accumulation, Exposure to Sediment, and Sensitivity to Change

The third parameter domain examines more local, reach-scale controls on channel morphology. Topics covered include: 1) channel gradients and habitat types, 2) wood accumulation types, and 3) intrinsic sediment exposure.

3.3.1 Channel Geometry, Habitat Types, and Sensitivity

Simple measures of channel morphology can provide useful estimates of habitat type (Bisson et al. 1982, Burnett et al. 2003) and likely channel responses to natural disturbances and landuse impacts (Sullivan et al. 1987, U.S.F.S. 2002). Channel morphology (i.e., pool-riffle, step pool, cascade etc.) is largely a function of channel size, gradient, and valley confinement (Kellerhals et al. 1976, Bisson et al. 1982, Rosgen 1994, Montgomery and Buffington 1997). These attributes can all be estimated with digital elevation data (drainage area correlates well with channel size), so that an initial estimate of channel types within a basin, and the proportion of each, can be obtained solely through analysis of the DEM.

Channel size and gradient are generally correlated (narrow channels tend to be steeper) (Leopold et al. 1964) so that gradient alone provides a useful measure for delineating channel types. Common channel types include bedrock–boulder cascade, boulder-cobble step pool, meandering pool and riffle, and braided (Figure 33). For example, meandering pool and riffle channels are often located in channels less than 2% gradient. Boulder and cobble floored, step pool channels generally range in gradient from 2 to 4%, and cascade channels are often in excess of 4% (Grant 1990). *TRIAD* creates maps of channel gradients (Figure 34, A); the user can infer channel types using existing stream classification systems (e.g., Montgomery and Buffington 1997, Rosgen 1995) or based on site-specific field observations (Figure 34, B). Regionally specific channel classification systems can also be used, for example in

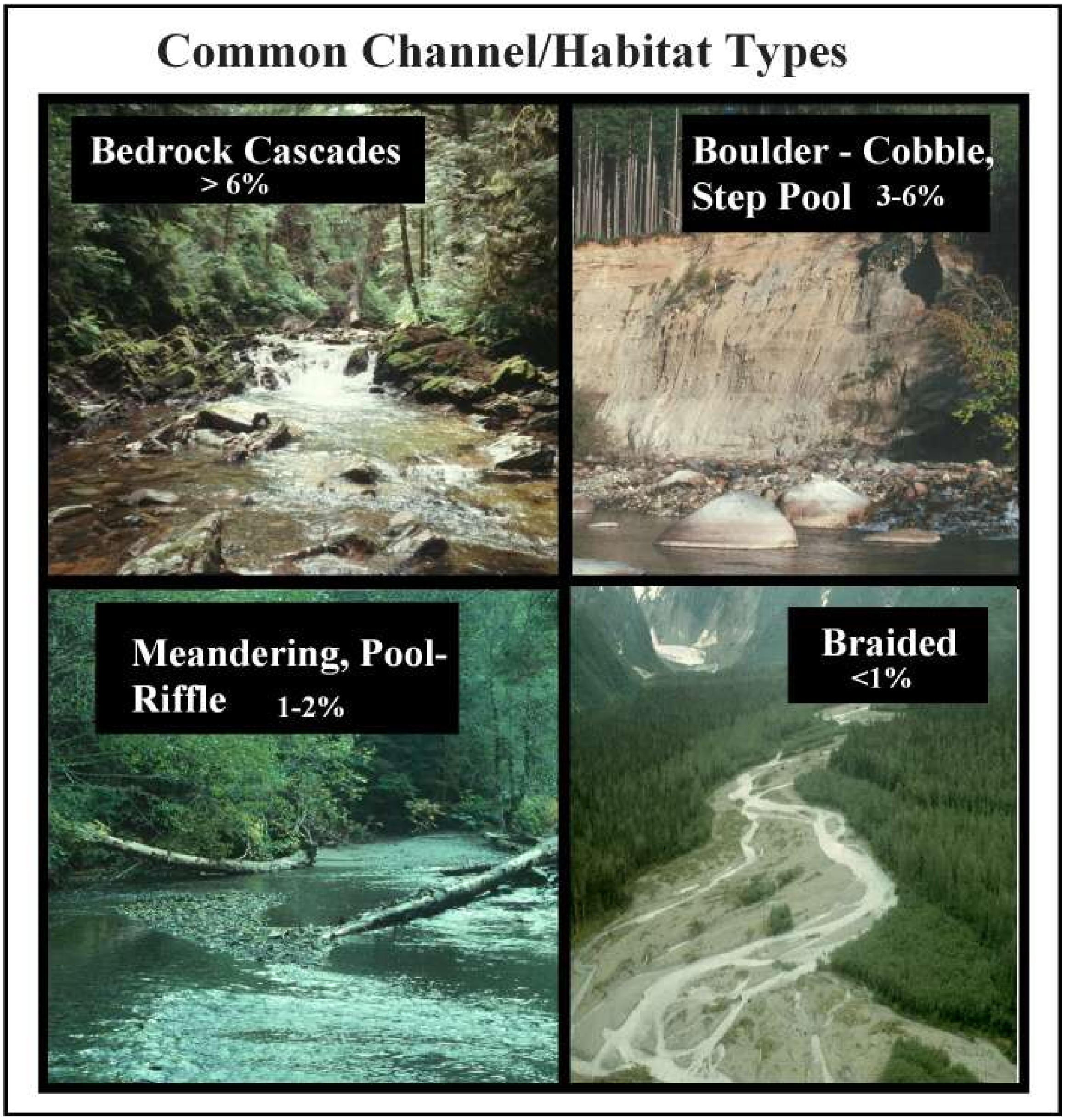


Figure 33. Estimates of channel gradient, valley confinement, and wood accumulations can be used to infer different channel types that are important to aquatic habitats.

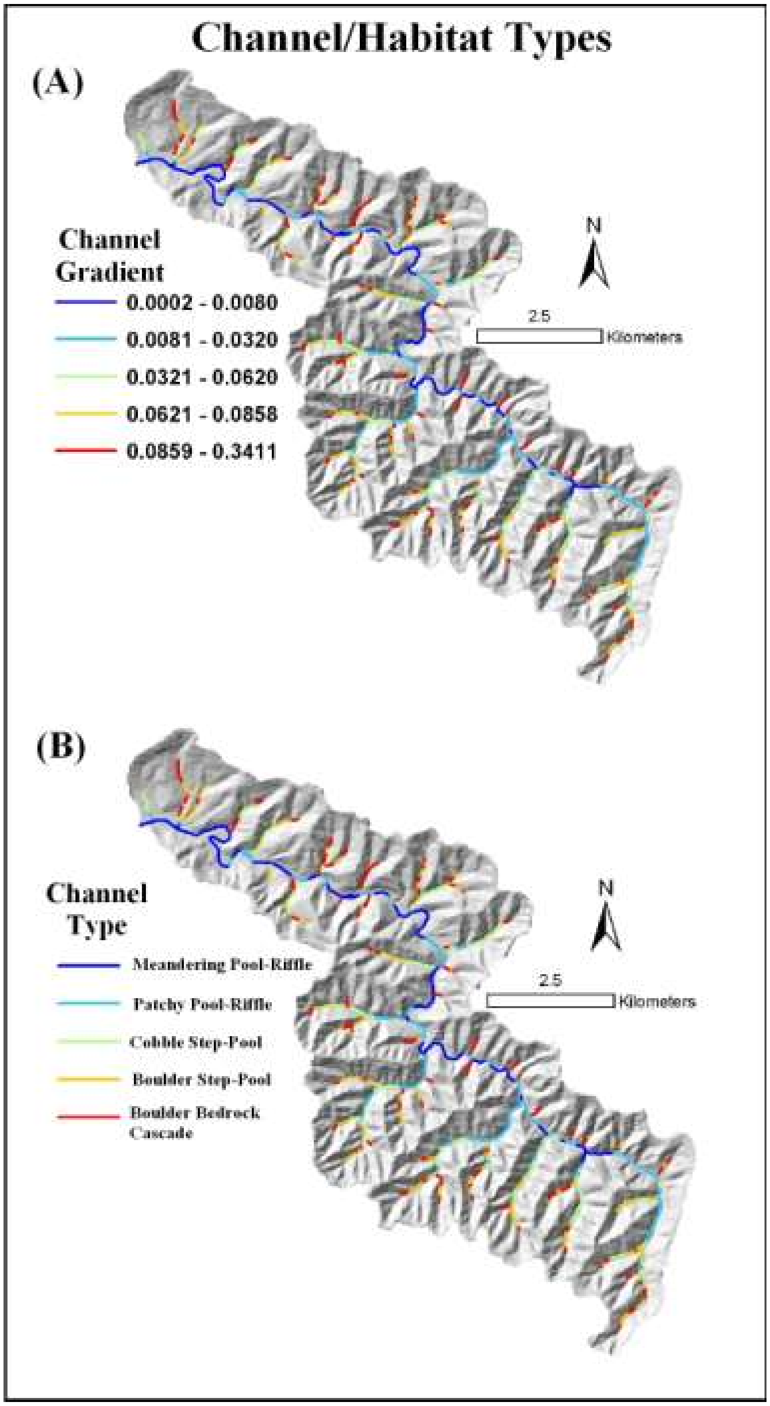


Figure 34. Channel gradient (A) can be a good proxy for different channel types (B), the relationship here shown in a 5th-order basin in the Oregon Coast Range. Other information such as wood accumulation types (See 3.3.2), valley confinement (Figures 29-32), near-stream topographic roughness (Figure 15), and lithology and erosion potential should also be used to delineate channel types. Aerial photography and field surveys are recommended.

southeast Alaska (Paustian 1992). Inferring substrate sizes is more difficult because of confounding factors that include lithology, wood accumulations, and disturbance history. Field recognizance (or the use of other databases) is recommended when linking particular channel gradient classes with substrate sizes to the overall environmental context of the channel (i.e., confinement, wood accumulations [see below], and bedrock controls, etc.). CDFs of channel gradients and inferred channel/habitat types (covering all 3rd- and higher-order, fish-bearing channels, e.g., Figure 4) comprise a queryable database in TRIAD that can be used to estimate the relative proportions of different channel types within a watershed (Figure 35, A). Predicted channel types can be coupled with other *TRIAD* parameters to infer other holistic habitat characteristics (discussed in Section 4.0).

Channel gradient is also an indictor of channel susceptibility to natural disturbance or land use related impacts. In general, lower-gradient channels in unconfined valleys are the most susceptible to channel aggradation, degradation, and instability associated with increases in sediment supply and floods (Miller and Benda 2000). Steep, bedrock, and boulder-floored channels are the least susceptible to channel disturbances (Figure 35, B). Hence, the proportion of the channel network most susceptible to changes due to flooding, sedimentation, and loss or addition of large wood can be queried using the CDFs of gradients (and valley confinement, Figure 30) in any watershed or across a population of watersheds. For example, the CDFs of channel gradient for three well-studied basins in the Pacific Northwest are shown in Figure 36. The effects of debris flows on all three systems have been documented and they reflect the differences seen in the CDFs. In Knowles Creek basin (Oregon Coast Range) where 55% of the third- and higher-order network is less than 2%, debris flows have major consequences on channel morphology including creating ponds, log jams, gravel accumulations, meanders, and boulder accumulations (Everest and Meehan 1981, Benda 1990). In contrast, in French Pete Creek basin (Oregon Cascades) where only 5% of its channel length is less than 2%, the boulder-bedded, step-pool channel is mostly resistant to debris flow impacts (because of high stream power) (Grant and Swanson 1995). Lookout Creek basin (Oregon Coast Range) has about 20% of its length in channels less than 2% (Figure 36) and the degree of morphological effects fall in between that of Knowles Creek and French Pete Creek basins and includes local channel widening upstream of debris flow fans (Grant and Swanson 1995).

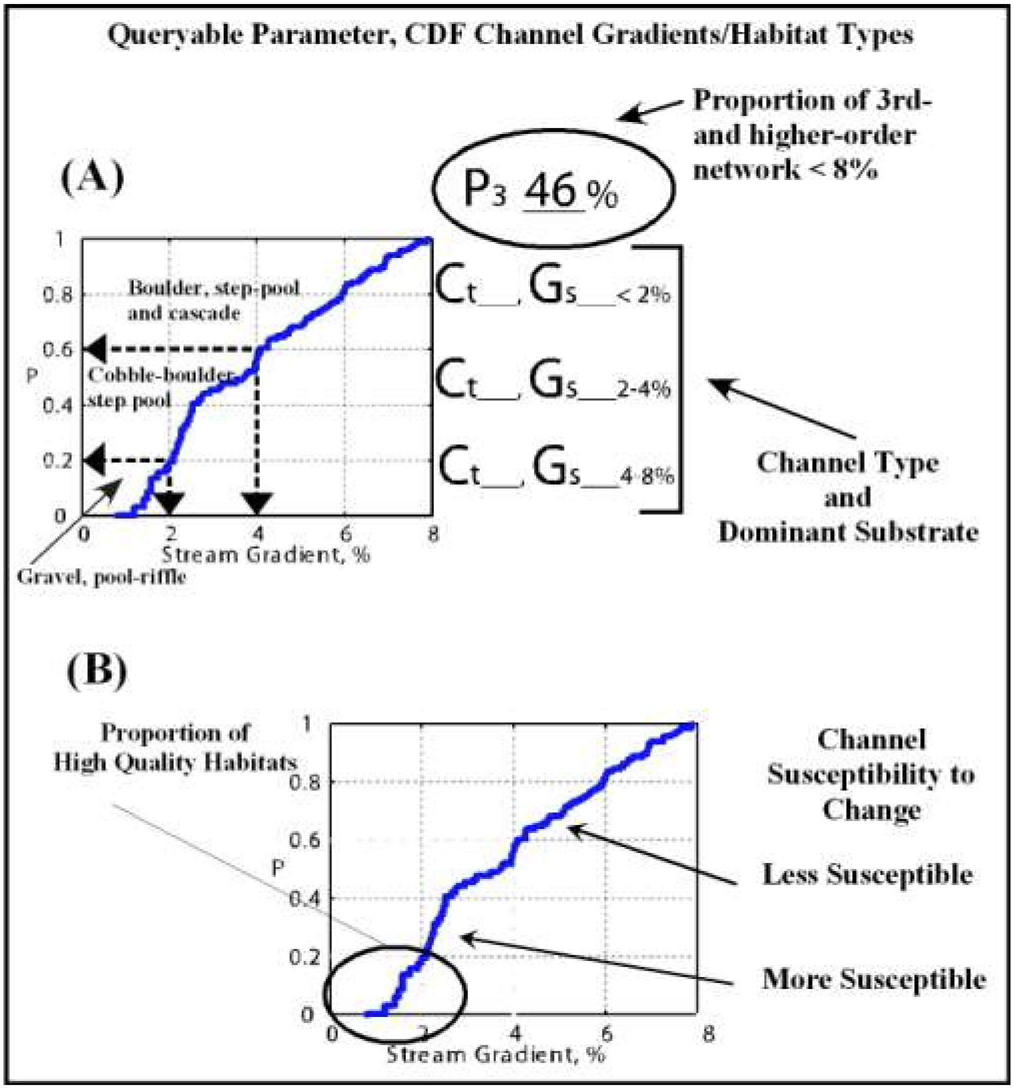


Figure 35. (A) Cumulative distribution functions (CDF) of gradient (for the third-and higher-order or fish-bearing network) can be used within a queryable database to search, sort, rank, compare, and classify river networks. Channel types (e.g., Figures 33 and 34) and substrate texture (i.e., boulder, cobbles, gravels) can be inferred or obtained from other databases or from field observations. (B) The CDF of gradients can be used to understand what proportion of the network is prone to channel changes during natural and human-generated sediment and flood related disturbances.

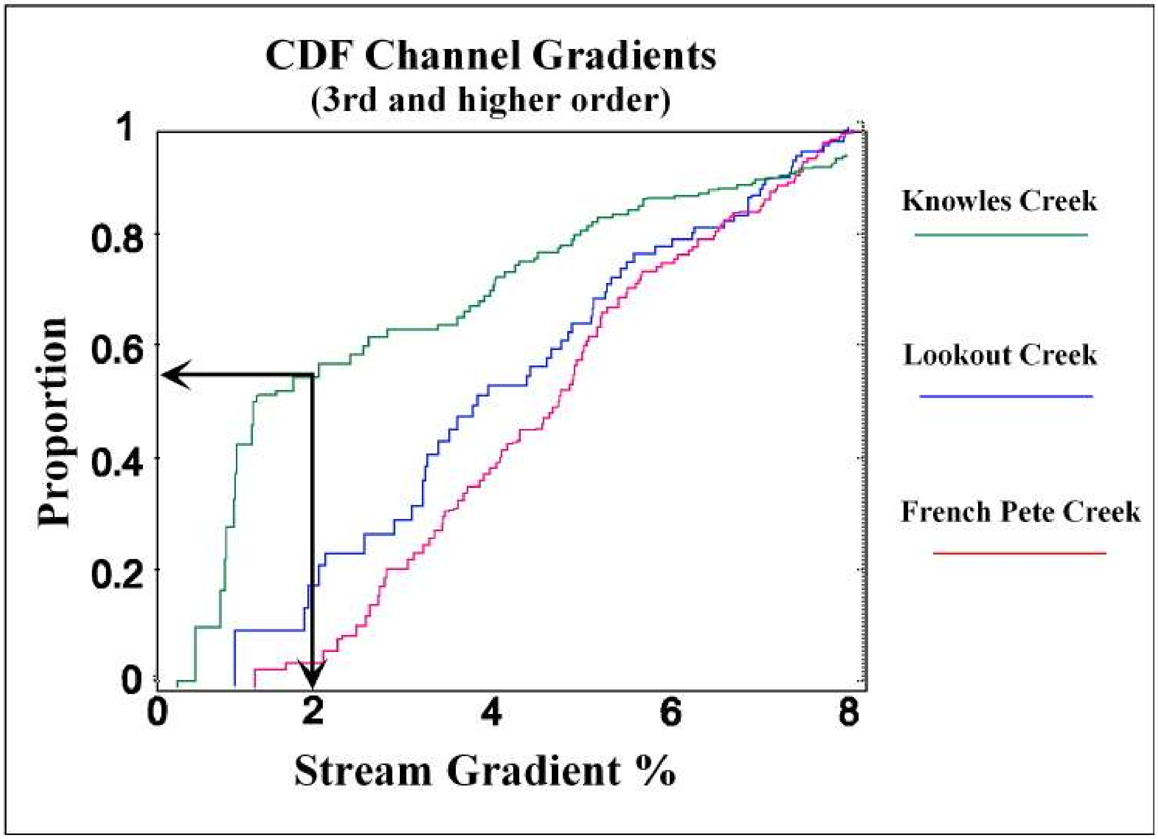


Figure 36. An example of how cumulative distribution functions (CDFs) can be used to contrast different fluvial systems. Shown are three well studied basins in the Oregon Coast Range and Oregon Cascade Range that are all susceptible to debris flows originating from steep, first- and second-order streams. Knowles Creek with almost 60% of its third- and higher-order network less than 2% is the most susceptible to debris flow impacts to channels that can include log jams, ponds, and gravel accumulations. In contrast, French Pete Creek has less than 5% of its network less than 2% gradient and is the least susceptible to debris flow-induced changes. Lookout Creek falls in between the two end member cases. For information on effects of debris flows in the three basins see Everest and Meehan (1981), Sedell and Dahm (1984), Benda (1990), and Grant and Swanson (1995).

Local reach-scale changes in channel morphology are also associated with landslides, tributary confluences, and transitions between confined and unconfined valley segments, as discussed previously. Heterogeneities introduced by these factors are not well represented in a distribution of channel types, but can be inferred from other TRIAD parameters. Measures of channel type, together with measures of heterogeneity provided by parameterizations of topographic controls on erosion, landslide abundance, density of channel confluences, and variations in valley width provide a more complete characterization of river environments needed for landscape analysis.

Channel width is another important attribute in estimating characteristics such as valley confinement and discharge. Predicting channel width requires regional regressions between channel width, a measure of drainage area, discharge, and/or precipitation (Figure 37).

Bedrock outcrops in channels are another important source of physical heterogeneity in some rivers and their representation by a single parameter can be used to rank their importance across a population of watersheds. In high-roughness watersheds (e.g., Figures 14 and 16), bedrock outcrops may be the dominant control on channel morphology. *TRIAD* indexes bedrock outcrops in terms of their relative abundance in river systems using either stream-adjacent topographic roughness as a proxy (e.g., Figure 14) or using field observations. Qualitative indices may include none, few, and many; "many" could refer to bedrock outcrops as the dominant feature influencing channel morphology. A river system dominated by bedrock outcrops may be more resistant to both natural disturbances and human impacts compared to pool-riffle systems with wood accumulations.

3.3.2 Wood Accumulation Types

Large organic debris in streams and rivers has been recognized as an important component in channel morphology and riverine ecology over the past several decades (Gregory et al. 1991). Woody debris in streams regulates and stores dissolved and particulate matter (Bilby, 1981) and creates temporary reservoirs of coarse sediment, thereby altering local channel gradients and channel morphology (Heede 1972, Megahan and Nowlin 1976, Keller and Swanson 1979, Bisson et al. 1987, Montgomery et al. 1995). Deposits of sediment stored behind logs create spawning areas for fish (Keller and Tally 1979, Sullivan et al. 1987). Pools formed in association with wood function as rearing and feeding areas for fish in the summer and as critical low-velocity refuge habitat in the winter (Lisle and Kelsey

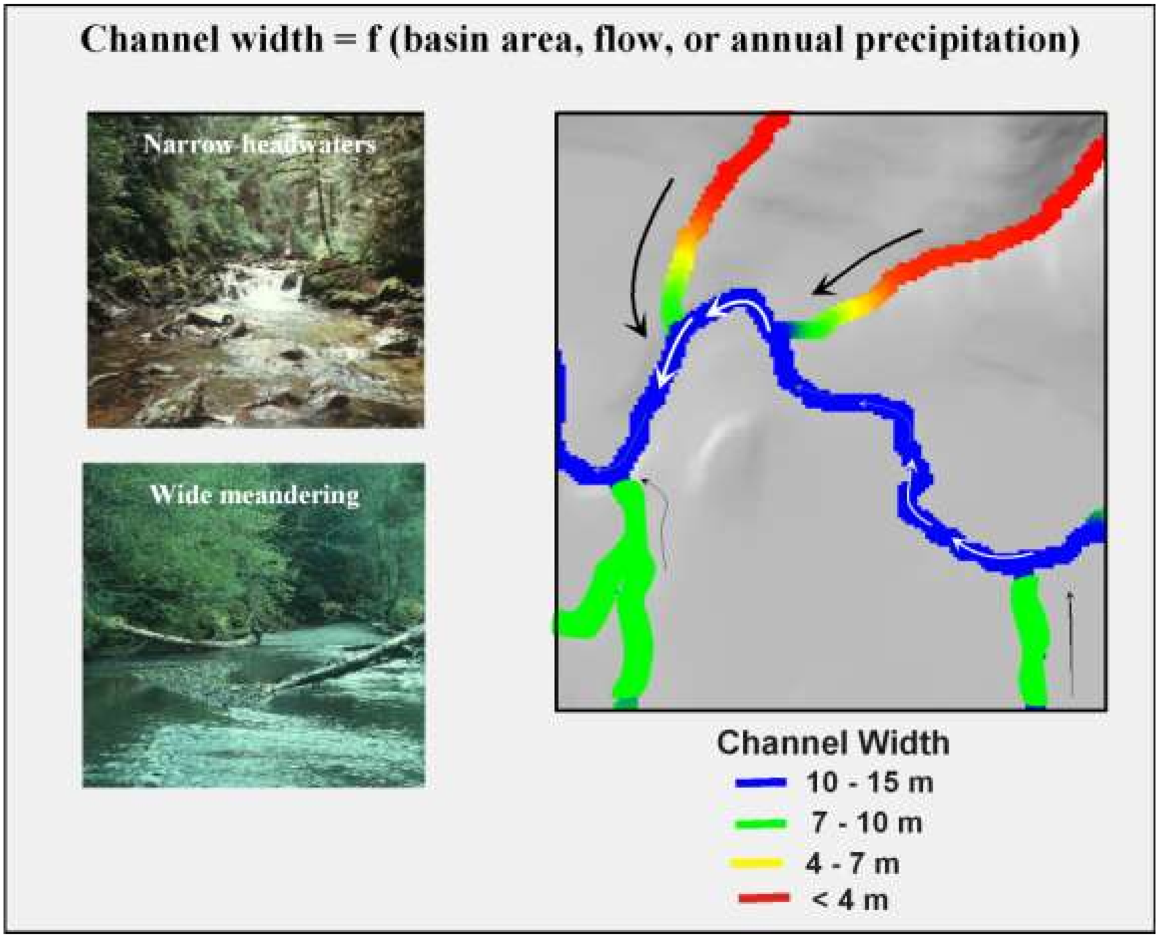


Figure 37. Channel width is important for interpreting channel types (e.g., Figure 34) and valley confinement index (i.e., valley width/channel width), and it is estimated using empirical relationships between channel hydraulic geometry and flow discharge and/or average annual precipitation.

1982, Dolloff and Reeves 1989). As a consequence, the role of woody debris in fish habitat and stream ecology has become a central theme in the management of forests (Femat 1993), environmental assessments (WDNR 1997), and the restoration of streams and rivers (Collins et al. 1994, Beechie et al. 1995).

Different portions of the channel network tend to have different types of wood accumulations (e.g., single pieces, jams) depending on the size of available woody debris relative to the size and wood transport capacity of the channel. Wood transport and hence accumulation types depend on several factors. Pieces that are transported tend to be shorter than bankfull width (Lienkaemper and Swanson 1987, Nakamura and Swanson 1993) and transport distances are limited by obstructions such as debris jams and boulders (Bilby and Likens 1980). Because channel width increases downstream, an increasing proportion of all wood becomes mobile if the distribution of recruited piece sizes remains approximately constant (Bilby and Ward 1989). Transport of wood is also affected by stream power (Braudrick and Grant 2000). Other complexities include diameter of logs, piece orientation, and the presence of root wads (Abbe and Montgomery 1996, Braudrick and Grant 2000).

The objective here is to minimize complexity in order to examine how a few factors (drainage area and slope [stream power], riparian tree height [e.g., log size], and channel width) impose constraints on spatial patterns of different wood accumulation types at the scales of watersheds. For instance, large, channel-spanning logs in small streams tend to stay where they fall. If the channel has sufficient power to transport wood, channel-spanning logs can form. Larger and more powerful channels will favor the formation of partial jams, scattered bar accumulation, or no accumulations at all.

Four wood accumulation types are defined based on field measurements obtained primarily in 100-km of streams in California (Benda et al. 2002b, ESI, unpublished data): 1) individual spanning logs, 2) spanning jams (greater than 70% of the channel is spanned), 3) partial jams (30 – 70% of the channel is spanned), and 4) scattered accumulations on lateral bars. Wood can only be measured in channels where it occurs and steep, high-energy whitewater streams generally have little stored wood in them. Hence the absence of data on wood accumulations in high-energy streams provides an indication where wood accumulation is not occurring. Consequently a fifth accumulation type is absence of wood storage.

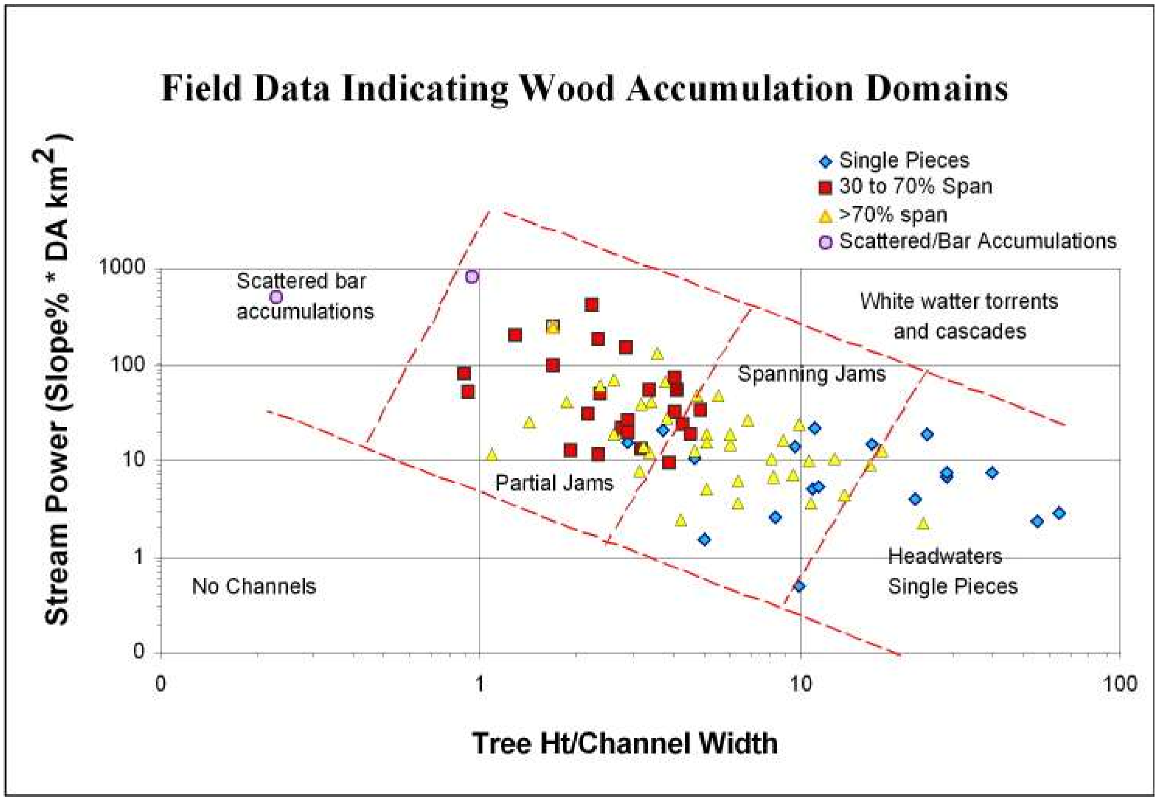


Figure 38. Wood in streams creates various types of accumulations that have implications for riverine ecology. In-stream wood can create different accumulations including jams that mostly or partially span a channel. In small streams, logs may be found in single pieces and in large rivers wood may be scattered laterally on bars and not create jams. In steep whitewater streams, no wood may accumulate. Field data from wood surveys are arrayed according to three variables including channel slope, width, and tree height (proxy for relative piece length), parameters that are known to influence wood transport. The distribution of the different wood accumulation types is analyzed probabilistically (see Figures 39 and 40).

Based on field surveys and observations, different wood accumulation types fall into relatively distinct fields in a plot of relative stream power against tree height scaled by channel width (Figure 38). The channel slope - drainage area product is used as a regional measure of relative stream power. The average height of riparian trees is used as a relative measure of log length, since piece sizes should correlate with the height of streamside trees (i.e., tall trees should break into longer pieces than short trees).

In Figure 38, fields for different accumulation types tend to be separated along lines perpendicular to the general log-log trend of the data points (reflecting the correlation between channel width and drainage area). By analyzing the varying density of points associated with each accumulation type the probability of finding a particular accumulation type can be estimated (e.g., Figures 39 and 40). To extend these results to a predictive GIS model, a DEM-derived estimate of drainage area and channel slope is employed, as previously described. Channel width is regionally calibrated to drainage area and mean annual precipitation. Site-potential tree height is used as a relative indicator of potential log size and is generally available in open-source digital databases (site class and vegetation maps). Thus, with a DEM and tree-height potential information the intrinsic probability of finding each of the four wood accumulation types can be estimated in any basin (based on mature trees at their average site class potential tree height); an illustration of this is shown in Figures 41 and 42. Besides map displays (Figures 41 and 42), the probability fields are used to calculate other descriptive basin attributes. For example, the channel length in a particular wood accumulation category is calculated. Dividing that value by total channel length gives the proportion of channels in various accumulation categories. This provides queryable data from which watershed to watershed comparisons can be made. As is the case with all *TRIAD* parameters, higher resolution data (i.e. tree height data) should produce more accurate predictions.

3.3.3 Intrinsic Cumulative Sediment Exposure

Channels increase their sediment storage when the supply of sediment to them increases from channels located upstream of them, including tributaries, or from adjacent hillsides. Increased sediment storage is typically viewed as a threat to aquatic habitats because the attendant channel changes may include increased lateral instability, fill and scour, and fine sediment intrusion into gravels. However, increased sediment supply can create habitats by

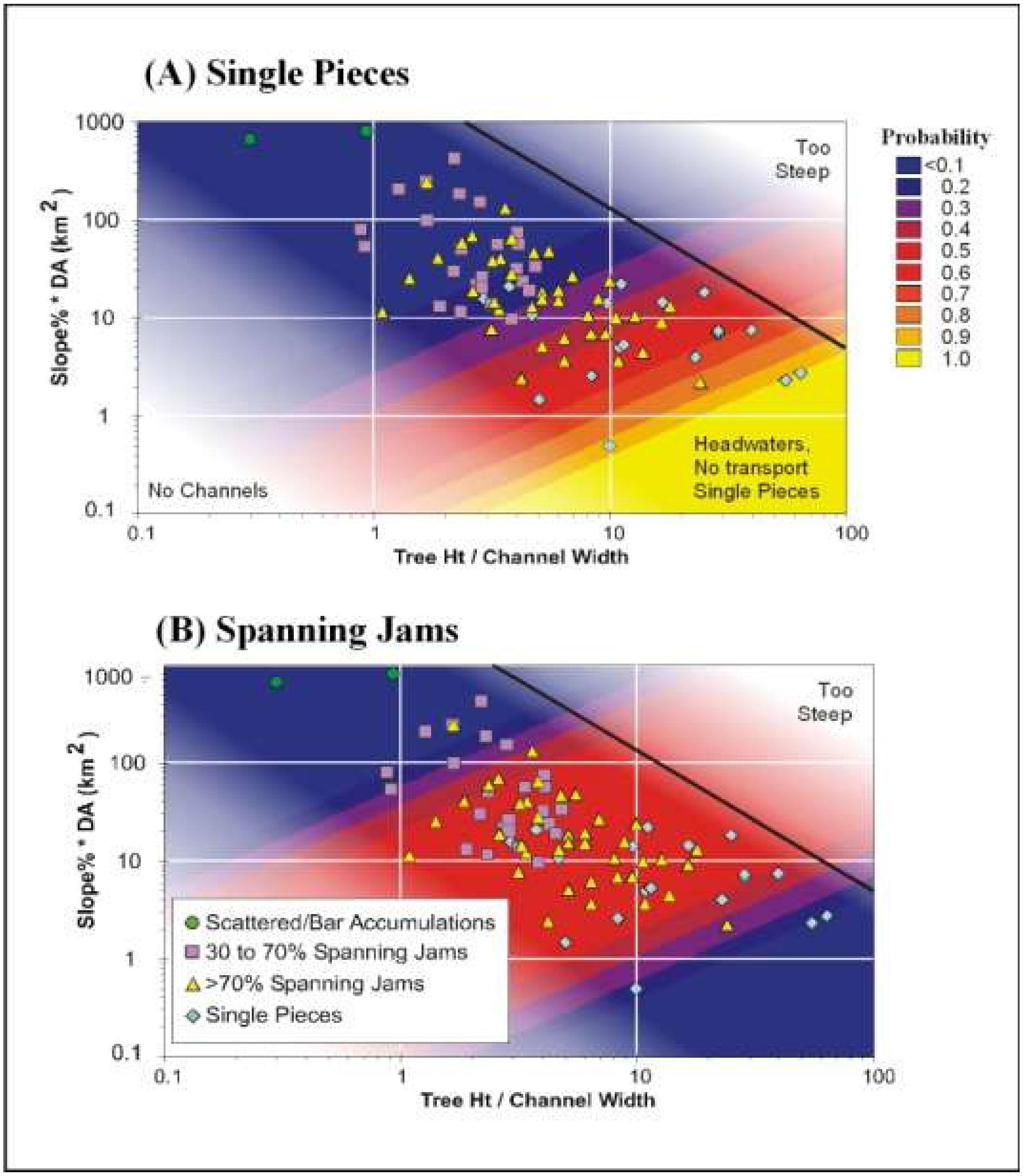


Figure 39. Data on wood accumulations (Figure 38) are used to create relationships that indicate varying probability of different wood accumulation types shown here for (A) single pieces (spanning, non mobile) and (B) spanning jams (> 70% of channel spanned by logs).

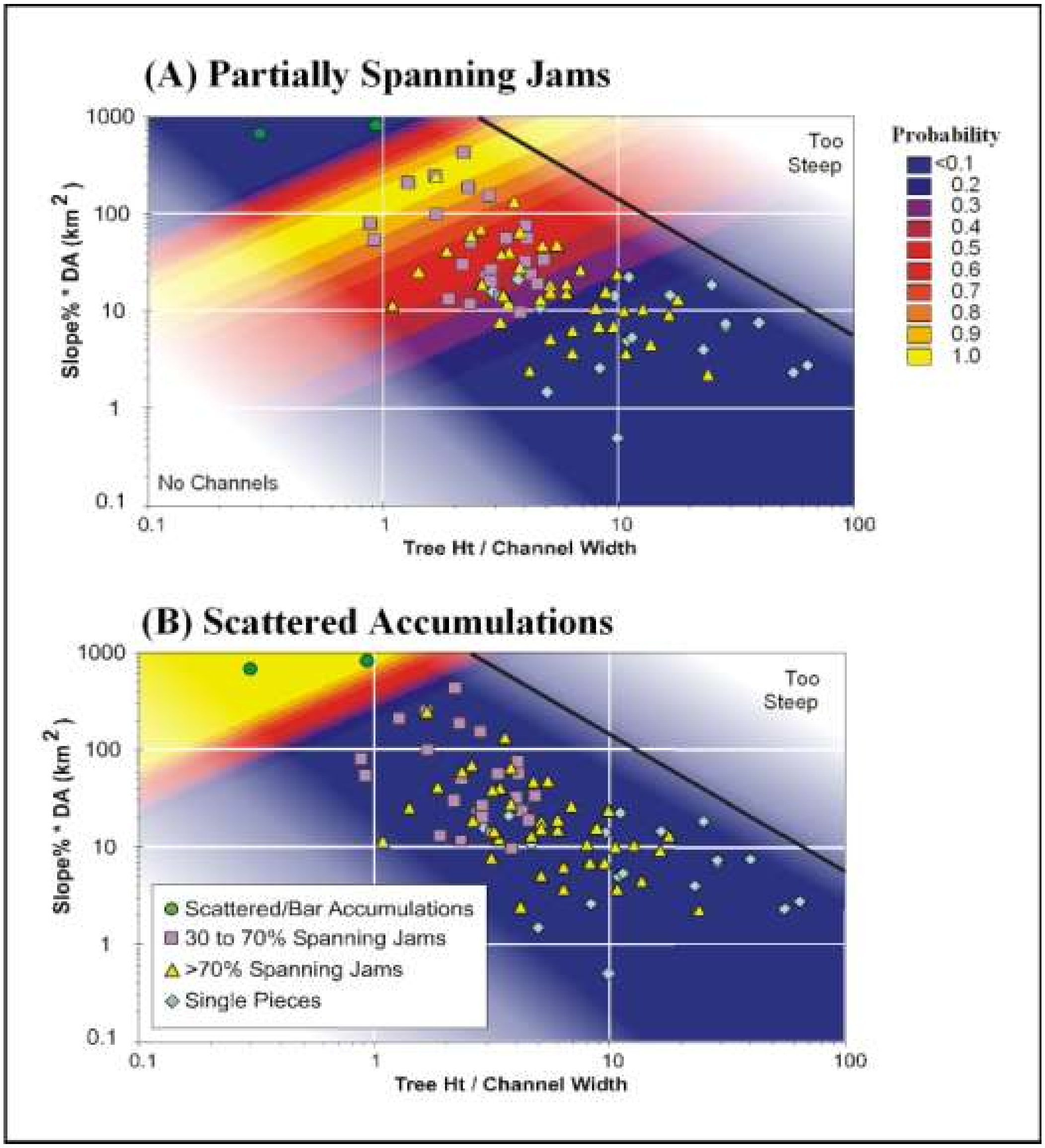


Figure 40. Data on wood accumulations (Figure 38) are used to create relationships indicating varying probability of different wood accumulation types shown here for (A) partially spanning jams (30 – 70% of channel width spanned by logs) and (B) scattered accumulations on bars.

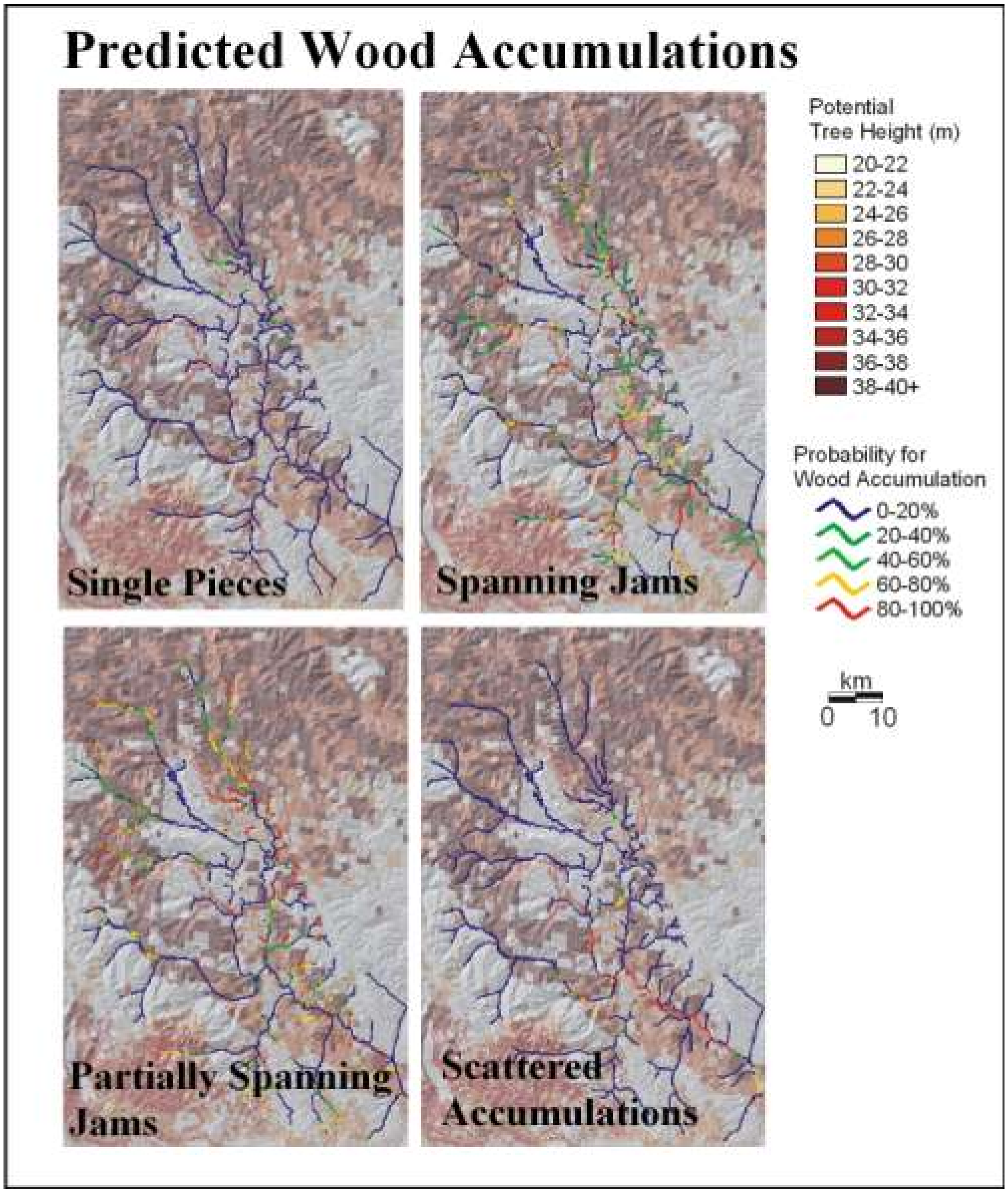


Figure 41. Applying the relationships for wood accumulations using data on channel gradient, channel width, and site potential tree height (Figures 39 and 40) yields probabilistic predictions for different wood accumulations. Site potential tree height is also shown (for non channeled areas). Since only the approximate 3rd- and higher-order network is shown on these maps, the prediction for single pieces (relevant to headwaters) is mostly omitted.

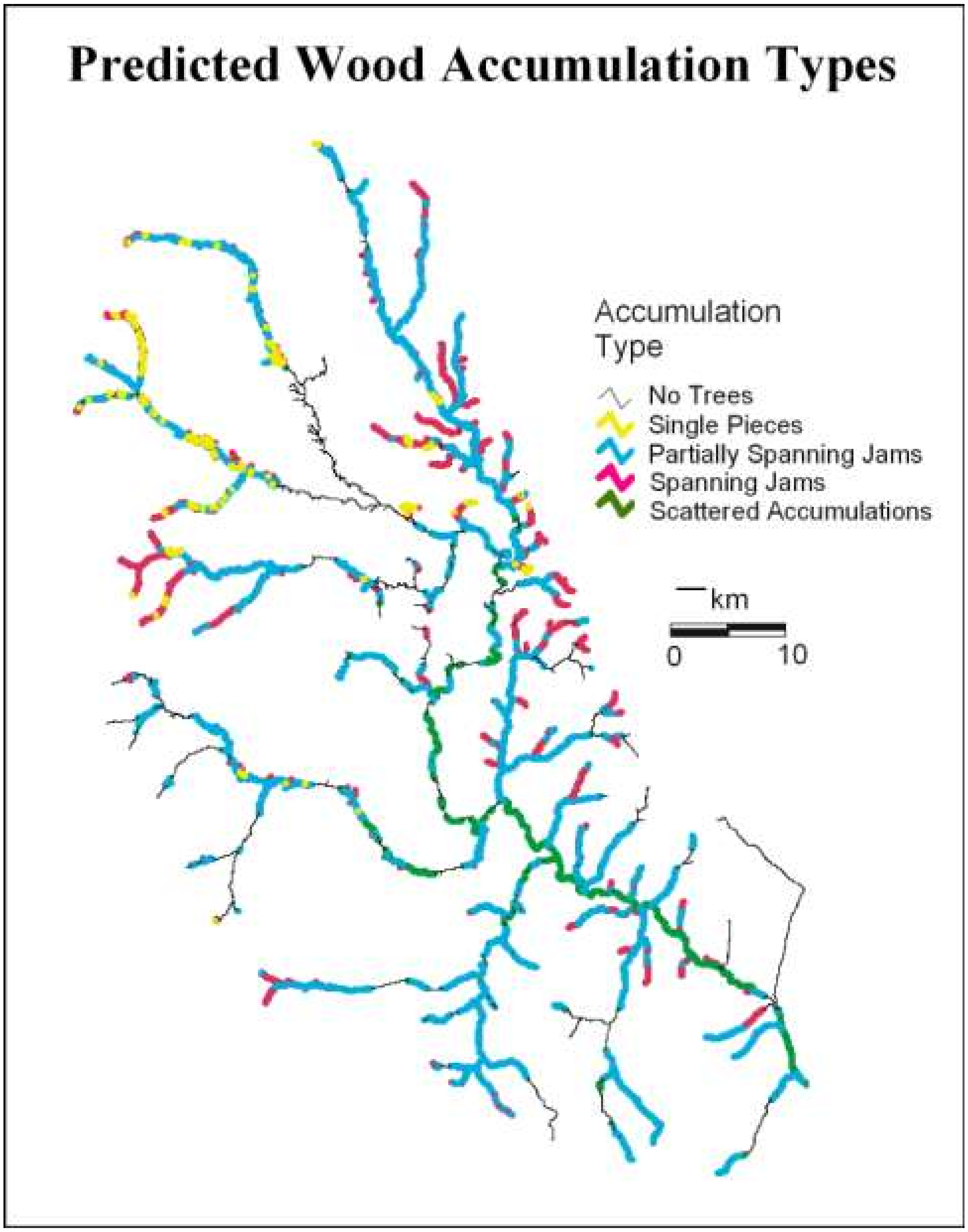


Figure 42. Using the probabilistic relationship for wood accumulations in Figures 39 and 40 and the predictions shown in Figure 41, the most likely type of wood accumulations can be predicted across large river basins. Cumulative distribution functions (CDFs) are generated that allows for cross-basin comparisons of wood accumulations types (i.e., channel lengths and relative abundance of certain types).

creating more bars, pools (increased depth of the deformable bed), side channels, floodplains, and terraces (Reeves et al. 1995, Hogan et al. 1998, Benda et al. 2003a). All sediment within channels that create habitats is derived from various forms of erosion. In mountain drainage basins, mass wasting is often the dominant source of erosion.

The potential for channel changes due to increased sediment supply depends on the location of major sources of sediment with respect to the channel reach of interest, the geometry of the channel (i.e., high gradient versus low gradient), the timing and magnitude of the sediment supply, grain size of the transported sediment, and antecedent sediment storage conditions (i.e., time since last erosion or sedimentation event).

TRIAD includes a measure of a channel's exposure to sediment that focuses solely on tributary sources of sediment and does not (by necessity) include the timing of erosion or sedimentation, grain size of transported sediment, and antecedent channel conditions. A channel's exposure to sediment also depends on channel geometry - high gradient channels are less susceptible to changes in stored sediment while low gradient channels are more susceptible (e.g., Figure 35, B). Interpreting the relationship among the likelihood of sediment exposure, channel geometry, and channel changes is the responsibility of the analyst; of course basin history can be included for particular applications. Because of the factors that are left out (i.e., timing of erosion, grain size, and antecedent conditions), *TRIAD* predicts the *intrinsic* cumulative sediment exposure.

Tributaries from the very smallest to the largest are likely the more significant sources of sediment to large (fish bearing) river channels. The potential for a tributary to create a sediment-related geomorphic effect in a river is based simply on the size of the tributary relative to the size of the mainstem (Section 3.2.1, e.g., Figure 19). Larger basins produce larger quantities of sediment and hence as rivers get larger downstream the size of tributaries required to create sediment-related effects must also increase. Because the supply of sediment from a tributary is finite, the morphological effect of increased sediment supply from a tributary in a mainstem should decline at some rate downstream (from the confluence). One effect of increased sediment supply from a tributary is a change (usually an increase) in the substrate size in the receiving channel proximal to the confluence and downstream. Hence, a measure of the downstream decay of sediment supply from a tributary in a receiving channel is how quickly the substrate sizes in the receiving channel returns to pre-tributary influx conditions. Substrate size effects initiated by an erosion source have

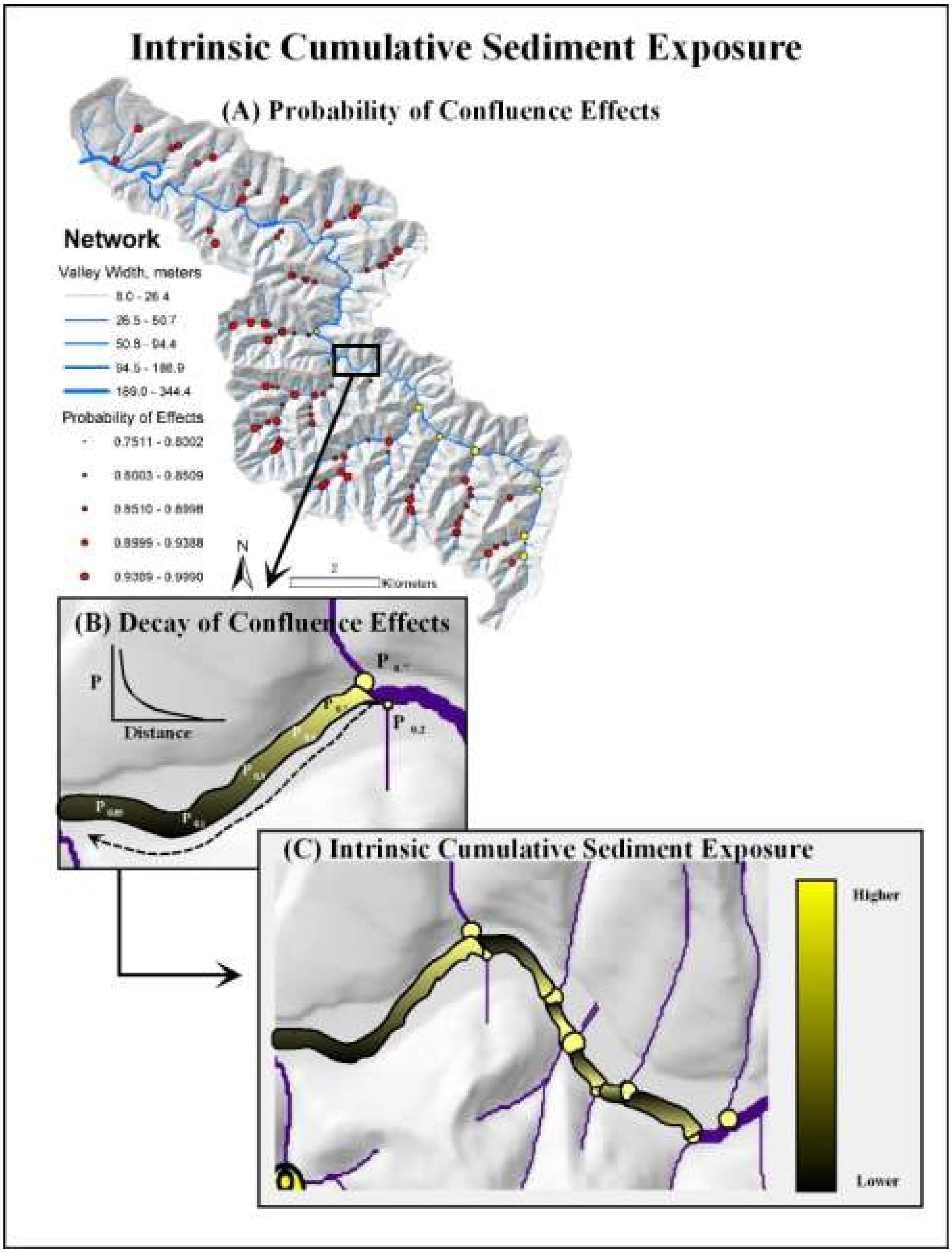


Figure 43. The intrinsic cumulative sediment exposure is calculated using the (A) probability of sediment-related confluence effects based on tributary size (e.g., Figure 19) and (B) a non-linear decay function between confluences. The probability of confluence effects is added as each confluence is encountered yielding a "cumulative" exposure to sediment index (C). The sediment exposure index is sensitive to basin size, basin shape, and local network geometry. An analyst should use other information including channel gradients, confinement, and wood accumulation types, etc. to evaluate a channel's risk to increased sediment.

been shown to decline in a non-linear fashion, a process referred to as 'attrition' or diminution' (Collins and Dunne 1989, Perkins 1989, Benda and Dunne 1997b, and Rice and Church 1998).

To predict a channel's intrinsic cumulative sediment exposure (from tributaries) TRIAD begins with the predictions of tributary confluence probabilities (Figure 43, A). The segments of mainstem channels that separate tributaries are viewed in terms of 'sedimentary links' (sensu Rice and Church 1998). Within these channel links, sediment effects decline non linearly with distance. Appropriate decay coefficients are determined empirically. Values in the literature span two orders of magnitude, ranging from ~0.05 to 5.0 km-1. It is possible for sediment effects from multiple tributaries to overlap. At each confluence a new probability is calculated in the receiving channel based on the residual probability (following its decay downstream) and on the addition of the new probability from the tributary; hence the reference to "cumulative sediment exposure" (Figure 43, C). Hence, the predicted exposure to sediment effects should vary considerably along channels due to variations in mainstem river size, tributary size, basin shape and network configuration, local network geometry, and general climate types (i.e., humid versus semi arid). An example using an exponential decay function with a coefficient of 0.5 km-1 is shown in Figure 44.

In addition to maps, the intrinsic cumulative sediment exposure can be incorporated into a single-value to describe its potential in a basin for comparative analyses. Multiplying the probability of sediment exposure by reach length, and summing over all reaches, provides an estimate of the length of channels with varying probability of sediment exposure in a basin. Cumulative distribution functions can also be used, indicating the proportion of channel length with differing probabilities of exposure.

3.4 Fourth Parameter Domain: Climate-Driven Disturbance

The three previous parameter domains are represented as temporally-averaged attributes of landscapes and riverscapes, even though many of the parameters can be used to help understand watershed dynamics, such as erosion, sediment exposure, and channel response, etc. To understand the dynamic or disturbance-related aspects of hillslopes and riverine habitats requires information on climate, in particular the high magnitude or extreme characteristics of precipitation, floods, fires, and erosion. In this fourth and final domain of *TRIAD*, the characteristics of a landscape's climate are described, including 1) precipitation,

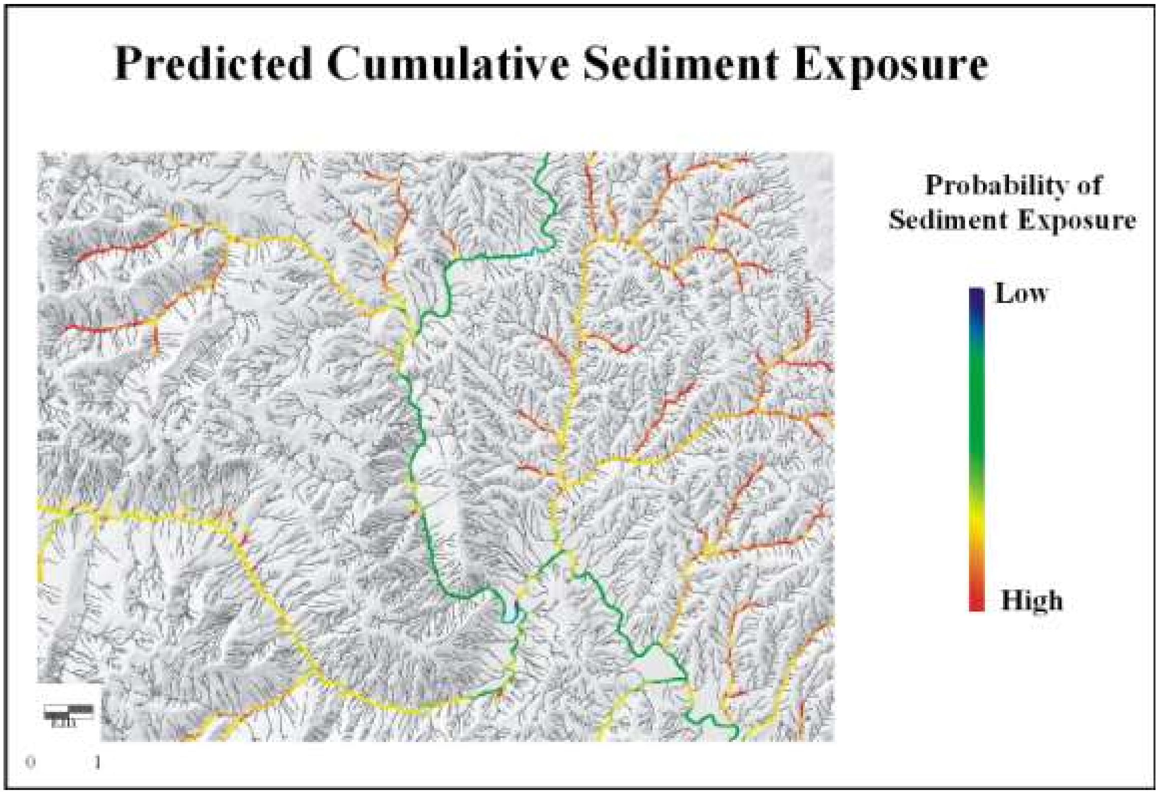


Figure 44. The cumulative sediment exposure is predicted using the relationship shown in Figure 43. The spatial variation in intrinsic sediment exposure across a watershed could support decision making by watershed scientists and planners regarding resource management, risk assessment, restoration, and monitoring.

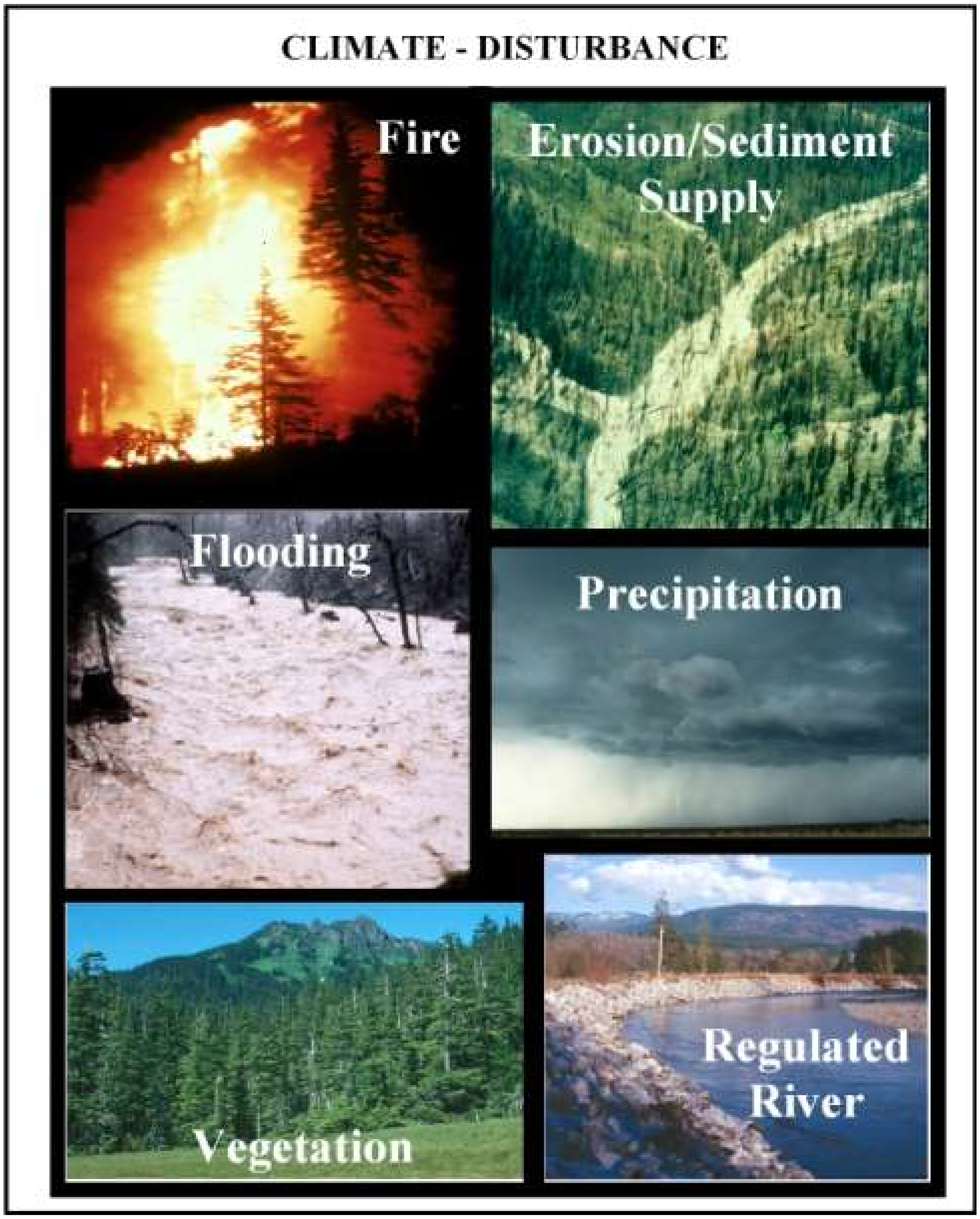


Figure 45. The fourth and final parameter domain of the Terrain Inventory and Resource Analysis Database is climate-driven disturbance. The climate domain includes information on high magnitude or extreme characteristics of precipitation, floods, fires, and erosion. Other related information includes vegetation and the degree of river regulation. These parameters can indicate the role and importance of natural disturbance in riverine environments and the potential for human disturbances to impact aquatic resources.

2) fires, 3) floods, and 4) erosion or sediment supply (Figure 45). Vegetation is also included since it provides an overall environmental context and is often important in understanding the relationship between climate and geomorphology. In addition, rivers that are regulated by engineered structures such as dikes and dams significantly impact natural variability in channel process and form, and hence it is included in *TRIAD*. Moreover, disturbances, such as floods and post-fire erosion can be viewed as a form of natural watershed restoration in the context of natural ecosystems.

Understanding the interrelationships among climate, disturbance, and riverine ecosystems requires combining information on climate attributes described in this section with parameters from the three previous domains. This requires certain levels of professional training and experience.

3.4.1 Overview

To understand how a landscape's climate is related to erosion, variable sediment and wood supply, and the fluvial dynamics of riverine systems, it is necessary to consider a basin's disturbance regime (i.e. the stochastic character of climate that triggers erosion and floods, etc.) (Figure 45). Disturbances such as storms, floods, and fires commonly trigger punctuated erosion by various forms of mass wasting in mountain drainage basins in North America, including the southwestern chaparral of California (Rice 1973), California Coastal Ranges (Kelsey 1980), other coastal rainforests of Pacific Northwest, British Columbia, and Alaska (Dietrich and Dunne 1978, Sidle and Swanston 1982, Straub 1998), Appalachian Mountains (Hack and Goodlett 1960), and in the intermountain region and southwestern highland deserts (Meyer et al. 1995, Wohl and Pearthree 1991). In forested landscapes, fires also can lead to large and punctuated recruitment of woody debris to streams and set the age structure of riparian forests that influences long-term wood recruitment (Benda and Sias 2003). In addition, extreme floods are largely responsible for the creation of riverine environments that include secondary channels, log jams, islands, floodplains, terraces, and fans (Kochel 1998).

Erosion processes deliver sediment to stream channels that is subsequently redistributed downstream by intermittent floods. Sediment from many sources, distributed throughout the basin, is thus routed through a branched channel network. Fluvial and riparian landforms are built of water-carried sediment and their physical characteristics (e.g., bed texture, sediment depth, terrace height, fan size) and the frequency with which they change are governed by the rate at which sediment is supplied and routed from upstream, fluctuations in that rate, and opportunities for valley-floor storage of sediment, all parameters that vary with basin size.

Therefore, a basin's disturbance regime related to fluvial processes is defined by the frequency, magnitude, spatial distribution, and composition of erosion and sediment transport events. Several key aspects of a basin's stochastic climate and geomorphic response allow one to infer the relationship between extreme events and riverine environments. Various parameters are used to characterize climate-driven disturbance and these can be interpreted within the context of other *TRIAD* parameters to understand the role and importance of natural disturbance as well as the potential of human disturbances to impact river environments. The rich topic of natural disturbance deserves a comprehensive discussion that is beyond the scope of this manual. What follows is a brief overview of the major disturbance parameters included in *TRIAD*.

3.4.2 Precipitation Regime

Precipitation (rain or snow) triggers virtually all erosion in a watershed. In general, the largest storms are responsible for most of the geomorphic work, including the formation of most fluvial landforms in mountain drainage basins (Swanson et al. 1988, Kochel 1988). A characterization of precipitation must therefore include some indication of 'large' storm magnitudes. *TRIAD* indexes precipitation using mean annual precipitation, climate type, in terms of rain, snow melt, or spring fed regimes, and the maximum recorded 24-hour precipitation. In general, rain-type climates, with high maximum 24-hour precipitation, are associated with the most dynamic landscapes and erosion regimes, with variable erosion rates, large channel-changing floods, and episodic construction of fans, terraces, and floodplains. In contrast, spring-fed systems may have few channel changing events with most fluvial landforms created by floods of low to moderate magnitude. However, snowmelt climate that is often characteristic of the inner-mountain western United States may include sporadic and intense thunderstorms, including following fires that can create large flash floods. This aspect of climate is included in the analysis of fires and floods below.

3.4.3 Fire Regime

Fire is a key control on the age and species structure of forests (Van Wagner 1978), on erosion, and on recruitment of organic debris to channels. For instance, intense fires create hydrophobic soils that can greatly increase surface runoff, causing massive surface erosion with associated channel changes and formation of fans and terraces (Rice 1973). Loss of upland forests can result in increased landsliding by loss of root strength (Ziemer 1981). Variation in fire regimes across landscapes may lead to large differences in the recruitment patterns of trees to streams and rivers (Benda and Sias 2003). Although fire behavior may be constantly varying in response to climate change and land use practices (Whitlock et al. 2003), topographic and regional differences in general fire regimes is useful for understanding the different vegetative and geomorphic role of fires across different landscapes.

TRIAD defines fire according to the average recurrence interval of fires of certain intensities. Average fire recurrence intervals can vary from multiple centuries in humid temperate climates to several decades in semi-arid regions (Agee 1990). Fire intensity refers to the degree of vegetation death and includes stand-replacing fires, common in humid temperate landscapes, to under-burns that are more prevalent in drier climates (Skinner and Chang 1996). Although fire frequencies and intensities vary by aspect and geographic position (ridge vs. valley floor) within a single watershed that might be important from certain perspectives (Morrison and Swanson 1990, Benda et al. 1998), *TRIAD* employs a basin averaged fire regime for simplicity. Additional complexities can be added by the analyst.

3.4.4 Stream flow and Flood Regime

Various attributes of a watershed's stream flow have important implications for riverine ecology. For example, variation in stream flows, ranging from floods to low flows, can influence population and community dynamics of stream systems. Different types of stream flow variation, patterns of flooding, and extent of intermittency should also govern certain aspects of channel morphology as well as set the aquatic template for various stream dwelling organisms (Poff 1996). Moreover, the largest floods typically result in the largest changes in aquatic and riparian habitats thereby setting large-scale constraints on a riverscape (i.e., floodplains, terraces, etc.). A thorough treatment of hydrological controls on riverscapes is beyond the scope of this manual; for detailed discussions see Poff and Ward (1989) among others.

TRIAD indexes stream flow using the flow regime, average annual flow, and the flash flood magnitude index. *TRIAD* employs a stream flow classification systems developed by Poff (1996). Eleven types of flow regimes are recognized, ranging from "harsh intermittent" to "snowmelt" to "snow and rain" to "stable groundwater" to "perennial flashy". Rigorously assigning stream flow classification requires detailed analysis of hydrological data, such as flood frequency, seasonal predictability of floods, timing of flooding, and extent of intermittence, etc. (Poff 1996). Stream flow data are available from a variety of sources including EarthInfo and the U.S. Geological Survey; analysis of data can be accomplished by various means, including computer programs. In the absence of detailed hydrological analysis, the general stream flow regime can also be qualitatively surmised.

In addition to Poff's (1996) classification system, *TRIAD* employs information on a watershed's potential for flash floods since extreme floods are very important in shaping various aspects of riverscapes (Schick 1988).Flash flood index is a measure of the difference between the average annual and higher flows (Beard 1975). Mean annual flood is generally an easy parameter to obtain using U.S.G.S. databases or from some other regionally calibrated flood frequency curves. The flash flood index is calculated from the standard deviation of the logarithms of annual maximum discharge as $FF = X^2/(N-1)$ where $X = X_m - M$, X_m is annual maximum discharge, M is mean annual discharge, N is number of years of record, and X, X_m, and M are all given as logarithms. Rivers with high FF values (0.4 – 0.9) are located in semi-arid to arid areas. Low values (0.1 – 0.4) occur along northwest coastal areas and in the north central states. High FF values translate into a flooding regime characterized by low frequency and extreme flash floods that may significantly alter channel characteristics and destroy, or create, fluvial landforms along valley floors. For example, in California, FF ranges from 0.2 on the humid north coast to 0.9 in the more arid southern extremity.

3.4.5 Erosion Regimes

The erosion regime of a watershed exerts a strong influence on river environments, including channel morphology that responds to changing rates of sediment supply. For example, the role of channel confluences on the morphology of mainstem rivers can wax and wane in response to the flux of sediment out of tributary basins (Benda et al. 200b3). In addition, terraces and fans are built during periods of high sediment supply. High erosion rates can also lead to gravel-rich channels and braided morphology (i.e., transport limited channels). In contrast, low erosion rates can lead to sediment impoverished, bedrock or boulder-floored channels. From an ecological perspective, basins with intermediate to high erosion rates may contain a greater diversity and abundance of valley and channel landforms, but may also be more susceptible to land use acceleration of erosion. In-stream monitoring and restoration activities may be problematic in watersheds with high erosion rates, due to channel instability and large fluctuations in sediment transport. In *TRIAD*, the erosion regime is described by mean sediment yield and by the variability in sediment yields (the occurrence of extreme events) represented by the skew of the probability distribution of annual sediment yields.

The average sediment yield (t km^{-2} yr^{-1}) of a watershed can be estimated from suspended sediment or turbidity measurements (Ritter and Brown 1971), basin sediment budgets (Reid and Dunne 1996), radiocarbon dating of hillslope sediment reservoirs (Reneau and Dietrich 1991), cosmogenic dating of stream sediment (Kirchner et al. 2001), sediment accumulation in natural or human-constructed reservoirs (Sommerfield and Nittouer 1999), and measures of landscape uplift rates (Milliman and Syvitski 1992). Estimates of average erosion rates are available for many watersheds in the United States (Larson and Sidle 1980) or they can be inferred from erosion or sediment budget studies conducted outside the target watershed. Across the western U.S., mean erosion rates can vary from a maximum of about 6,000 t km^{-2} yr^{-1} in the north Coast of California (C.R.W.Q.C.B. 2002) to a few hundred in other mountain landscapes (Granger et al. 1996). Mean erosion rates may be less than 100 t km^{-2} yr^{-1} in low-relief landscapes.

Punctuated and extreme events construct many river landforms and hence the variability in sediment yield is key for understanding the role of erosion on riverine ecosystems (Benda et al. 1998, U. S. F. S. 2002). Determining the variance of an erosion regime, in the form of the skew of the probability distribution, is more difficult than estimating its mean. Accurate estimation of variance would require a long time series of sediment yield data (10^2 – 10^3 yrs). Stratigraphic analysis of sediment layers in depositional basins (ponds, lakes, estuaries) can provide a proxy for a detailed time series of sediment yields (Sommerfield and Nittouer

1999). Another approach is the construction of stochastic simulation models of basin erosion regimes that estimate the probability distribution function (PDF) of sediment yields, from which the skew can be calculated (Benda and Dunne 1997, Istanbullouglu 2002, Gabet and Dunne 2003). However, simulation models are available in only a few landscapes. Yet another approach is the use of cosmogenic dating of stream sediment to estimate the longer-term (3000 – 8000 yr) mean erosion rate (Kirchner et al. 2001). The difference between the cosmogenic longer-term average and shorter-term (decadal) average of erosion rates (obtained from field-based sediment budgets and sediment monitoring stations) can provide an indication of the skew of the probability distribution of erosion rates in the present climate. This requires an assumption that the cosmogenic rate reflects erosion frequencies and magnitudes that are approximately comparable to contemporary, decadal rates. For example, the longer-term average (cosmogenic) erosion rate in the Idaho Batholith is 17 times higher compared to the shorter-term average decadal rate (Kirchner et al. 2001). This was interpreted to mean the erosion regime is dominated by high magnitude events probably linked to rare and intense wildfires. Hence, the skew of the PDF of sediment yields in mountain terrain in the Idaho Batholith would be high. A similar study in the central coast range of California revealed that the longer-term, cosmogenic erosion rates were only 2 to 3 times higher compared to shorter-term rates (Ferrier submitted). This indicates that the coastal California erosion regime is less punctuated compared to the Idaho Batholith, presumably because high intensity rainfall that triggers mass wasting occurs more frequently compared to wildfire-triggered erosion in Idaho.

Cosmogenic dating results (that measure averages) alone cannot indicate the skew of the probability distribution of erosion since a time series of erosion rates are necessary. However, cosmogenic results can be combined with computer simulation modeling to indicate the degree of skew that might be associated with measured differences between short and long-term average erosion rates. For instance, based on simulation modeling of post-fire rill and gully erosion in the Idaho Batholith, Istanbulluoglu et al. (2003) estimates the skew of the probability distribution of sediment fluxes to be approximately 20 (Erkan Istanbulluoglu, personal communication). Hence the large difference between long term and short term erosion rates determined from cosmogenic dating in the Idaho Batholith is likely associated with very high values of skew (Figure 46). In contrast, simulation modeling of landslide and debris flow erosion in the Oregon Coast Range (Benda and Dunne 1997) indicates a skew of approximately four, and hence this may reflect a difference between cosmogenic, longer-term rates and shorter-term erosion rates of perhaps 2 to 4, similar to the northern California example.

The magnitude of the skew of the probability distribution of erosion or sediment supply to channels has important implications for the role of disturbance in shaping riverine environments. In the mountainous Idaho Batholith, intense sheetwash and gully erosion following rare stand-replacing fires can trigger erosion in most gullies and headwater channels releasing massive quantities of sediment. The magnitude of erosion and sediment supply can completely fill 4^{th}- and 5^{th}-order valley floors, thereby restructuring valley floor morphology (Benda et al. 2003b), reflecting an erosion regime that is highly skewed (e.g., Figure 46, A). In contrast, intense storms and even fires in the Oregon Coast Range may only trigger failures in 5 to 10% of all potential landslide sites within a basin (Benda and Dunne 1997a), reflecting an erosion regime that is less skewed (Figure 46,B). Such moderate sediment releases may create sediment deposits mainly at tributary junctions with some limited channel aggradation off site (Figure 46, B). This latter pattern may also apply to the Oregon Cascades (Swanson et al. 1982) and to certain areas of northern California Coast Range (Kelsey 1980).

If quantitative estimates of the probability distribution of sediment flux are not available, the skew can be qualitatively estimated by other means. This is where combining information on hillslope steepness, channel gradients, fire and precipitation regimes, and professional training and experience can aid in estimating the episodicity of erosional events. For example, topographic controls on erosion will generally correlate with variability in sediment yield: low relief and low roughness topography may have a low skew, less than 2 (Figure 45, C). Gentle or flat landscapes may have a skew of less than 1 (Figure 46, D).

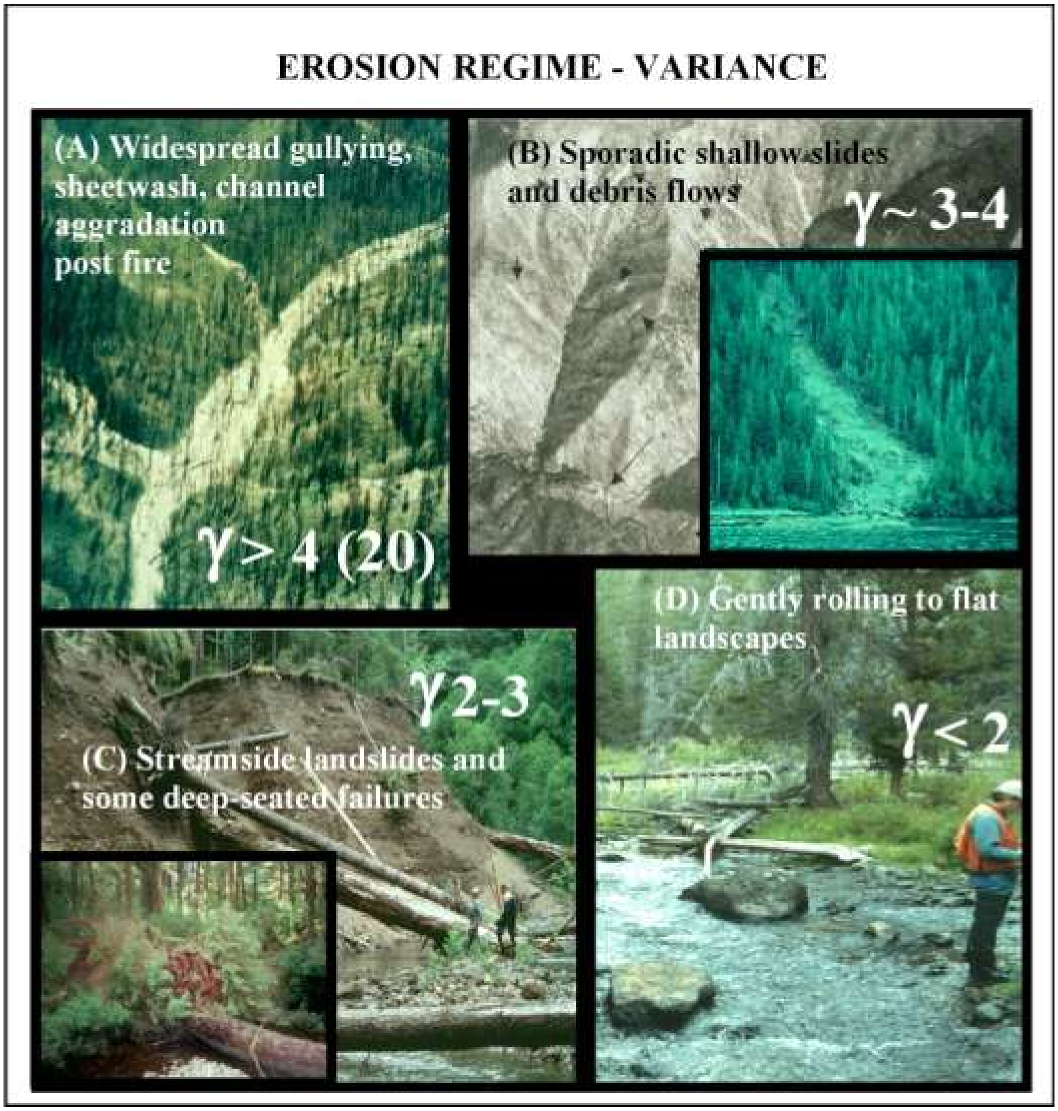


Figure 46. One of the climate-disturbance parameters is the erosion (and sediment transport) regime that should vary significantly across different landscapes. The important and hence role of extreme erosion events in shaping fluvial processes and hence ecological conditions is characterized by the skew of the probability distribution of erosion events over decades to centuries. The most extreme erosion regimes in the western U.S. may occur in semi arid areas (A). Less extreme erosion occurs in the humid temperate landscapes of the Pacific Coast (B). Lower relief and low gradient basins will have probability distributions of erosion with a low skew and hence have few geomorphically significant extreme events (C and D).

3.4.6 Sediment Transport Regime: Role of Basin Size

Estimating the skew of the distribution of erosion events provides a general indictor of how variable the supply of sediment is to stream channels. However, a channel network integrates sediment supply from thousands of point sources, including tributaries, and it modulates the frequency and magnitude of sediment transport by intermittent sediment storage (in channels, lateral bars, terraces, and fans), particle attrition, and the frequency and magnitude of floods. Hence, a channel's sediment discharge regime is affected by basin size. In general, the fluctuations in sediment transport should increase in frequency but decrease in magnitude with increasing drainage area downstream (Benda and Dunne 1997b) (Figure 47). This is due to 1) the size distribution of storms whereby the most intense storms have small spatial extent and generally affect small sub-basins rather than entire watersheds (Church 1998), 2) the number of sub-basins increases with increasing drainage area, each potentially capable of generating independent pulses of sediment that then mix and interact downstream, and 3) the diffusion and attrition of sediment pulses downstream due to selective transport, temporary sediment storage (e.g., behind bars, in log jams), and particle breakdown. Consequently, the skew of a channel's sediment discharge regime generally will be highest in the headwaters and decrease downstream (Figure 47, A-C) (Benda and Dunne 1997a). A highly-skewed sediment transport regime in the headwaters has certain implications for fluvial geomorphology. For instance, the age distribution of fans and other fluvial landforms such as terraces that are created during fluctuating sediment supply should be skewed toward older ages because of the rarity of large, forcing events. Sediment transport should be less punctuated with increasing distance downstream. A higher frequency of lower magnitude sediment transport events should cause a shift to younger ages of fluvial landforms such as bars, terraces, and fans (Benda et al. 2004b).

3.4.7 Sediment Transport Regime: Role of Network Structure

A key relationship between river networks and watershed disturbance is the expected downstream change in disturbance frequency and magnitude (Figure 47). A second key relationship between networks and watershed disturbance regime is the modulation of the sediment-related disturbance regime at tributary confluences (Figure 48). Reductions in

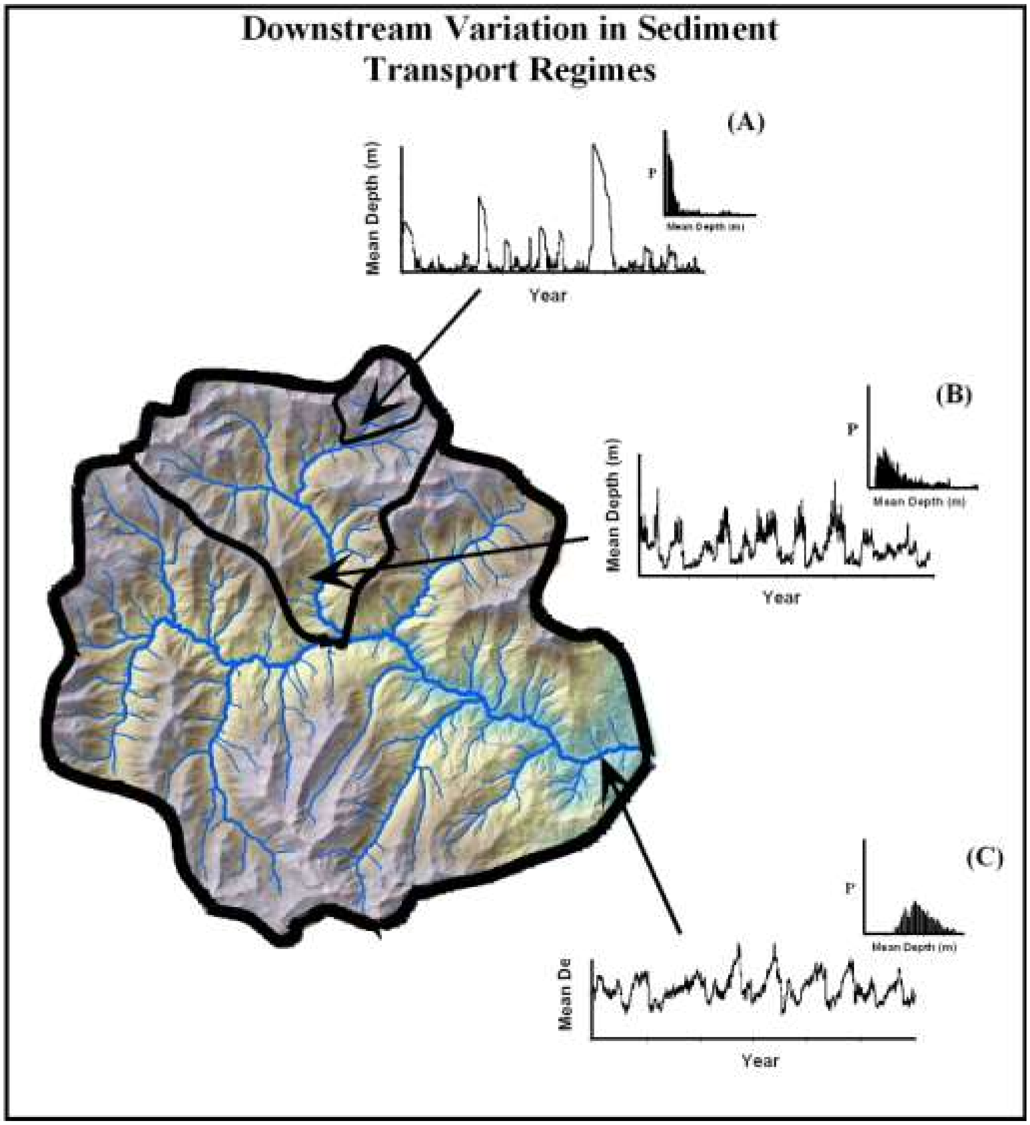


Figure 47. Frequency and magnitude of sediment-related disturbances vary with basin size, which influences the age distribution of fluvial landforms, particularly at confluences. (A) Disturbances are large but rare in headwaters leading to a higher proportion of older fluvial features. (B - C) Disturbances are more frequent but of lower magnitude further downstream in a network thereby creating a higher proportion of younger fluvial features and more persistent confluence effects.
Note the evolving shape of the probability distribution of sediment storage in channels (reflecting the supply and transport of bedload) from highly skewed in the headwaters (A) to log normal in the central part of the network (B), and finally to approximately normal downstream (C). This pattern reflects a property of the central limit theorem; see Benda and Dunne (1997a,b) for further details. Also the spatial pattern of the PDF of sediment storage in certain network types has implications for riverine diversity (see Benda et al. 2004a).

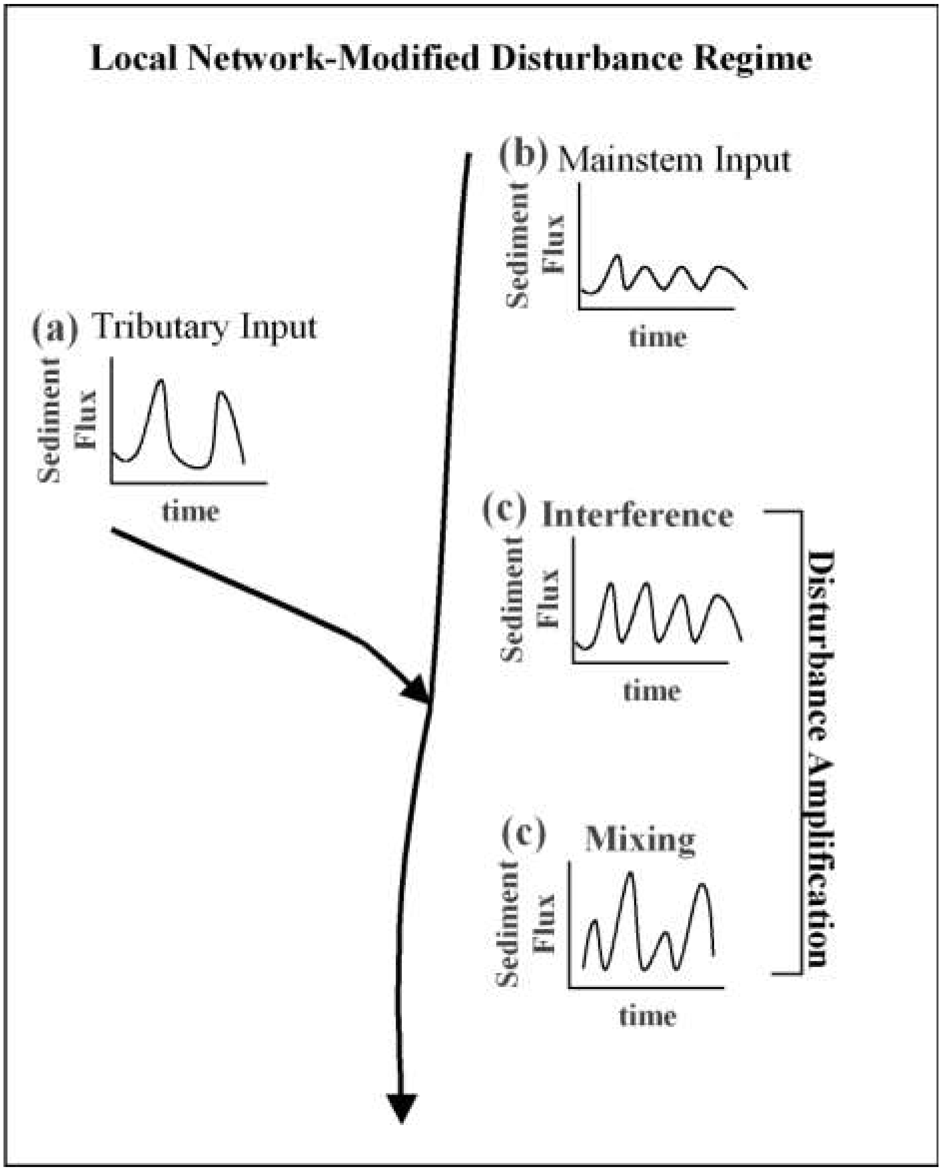


Figure 48. The sediment influx from tributaries (a) can modulate the frequency – magnitude relation of sediment transport and storage regimes in mainstem rivers (i.e., modify the channel's disturbance regime - b). Confluence-related sediment inputs can "interfere" with downstream sediment transport and magnify sediment transport and storage fluctuations *upstream of the confluence* (c). The abrupt influx of sediment from the tributary can lead to "mixing" proximal and *downstream of the confluence* causing both an increase in the frequency and magnitude of sediment fluctuations (d).

channel gradient and constriction of valley floors induced by fans interfere with the downstream transport of sediment and wood through mainstem channels, a process referred to as "interference". Interference can take the form of *amplifying* in-channel disturbances such as floods and sediment transport (i.e., increasing their magnitudes, Figure 48, C) because of increased lateral instability by bank erosion and channel meandering, and through increased vertical channel instability (Church 1983, Jacobson 1995, Benda et al. 2003b). In addition, disturbance frequency and magnitude can be increased immediately downstream of confluences because of the abrupt addition of sediment influxes from the tributary (Figure 48, D).

3.4.8 Vegetation

Vegetation cover type and percent cover are important determinants of landscape and riverscape behavior including various geomorphic processes such as resistance of soil to erosion, including landsliding (e.g., Figure 8) and the recruitment of large wood to streams. Consequently, *TRIAD* indexes vegetation according to general type using various vegetation classification systems, depending on the geographic area (e.g., Mayer and Laudenslayer 1988, Coastal Lands Analysis and Modeling [CLAMS, etc.]). Satellite imagery is presently being used by many agencies to create digital databases. Percent cover of vegetation is also indexed.

3.4.9 Regulated Rivers

Rivers that are dammed or diked, or rivers with large water extraction projects reflect large-scale alterations of hydro-geomorphic processes that can significantly impact many attributes of channels. In addition, historical large-scale placer mining altered significant areas of channels and valley floors, particularly in California (Mount 1995). Hence, regulated rivers are classified in the terrain analysis system as dammed, diked, water extracted, and placer mined when such information is readily available. Other classifications can be added.

3.4.10 Basin Connections

The overall ecological setting of watersheds is also dictated by where watersheds have their outlets. In other words, watersheds can outlet into other watersheds, into lakes, reservoirs, oceans, fjords, and closed saline basins. *TRIAD* includes reference to basin connections including closed (no other watersheds draining into them), open (watersheds draining into them), lakes, reservoirs, oceans, fjords, and closed (saline) basins.

Because of the ecological importance of estuaries, they are included as a separate parameter. Information on bathymetry, surface area, length, overall morphology, the ratio between estuary area and watershed area, and whether they are tidal or wave dominated is included as parameters (Figure 49)

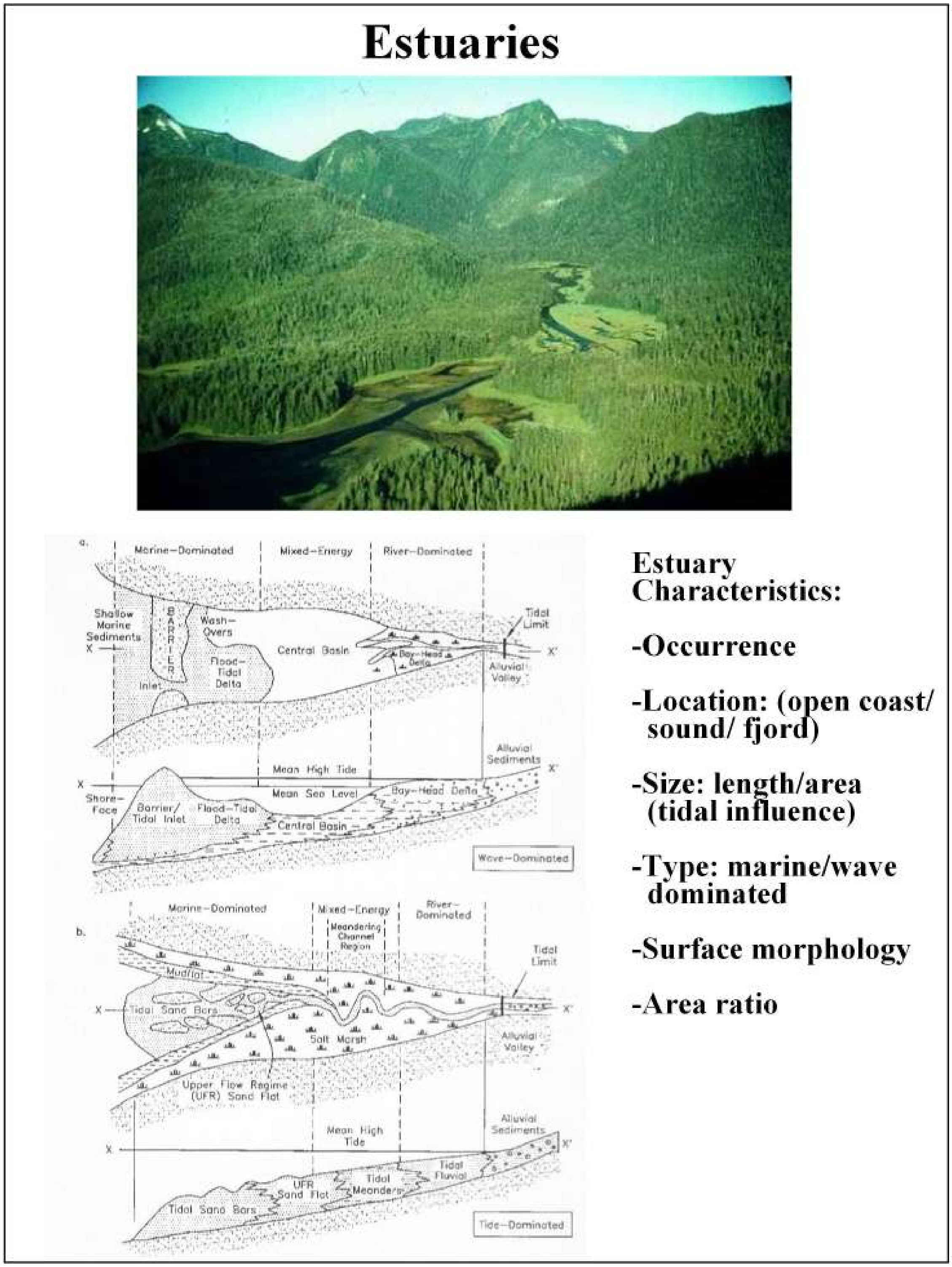


Figure 49. Estuaries are an important geomorphic and ecological feature in many landscapes that drain into oceans, sounds, and fjords. Estuaries can be mapped and classified occurring to their location, size, type, and surface morphology. This information can be put on maps or in queryable databases.

4. DECISION SUPPORT: POTENTIAL APPLICATIONS FOR RESOURCE MANAGEMENT

TRIAD parameters describe physical attributes of watersheds and their river systems. The parameters, either map-based information, CDFs, or single value watershed attributes (e.g., Figure 3), can be used to make ecological interpretations of river systems, such as the genesis and types of aquatic habitats, diversity of habitats, erosion potential, and a stream's potential exposure to sediment fluctuations. Hence, *TRIAD* parameters, singly or in combination, can help decision making in natural resource management, including: 1) stratifying watersheds for varying intensities of land management, including fuels management, 2) delineating prime areas for conservation, 3) targeting restoration, 4) prioritizing watershed and in-stream monitoring and research programs, and 5) extrapolating the results of such programs to other watersheds (Table 1). These applications can occur at the scale of individual watersheds (HUC 6^{th} field, for example) or at the scale of populations of watersheds (dozens to hundreds) within a single landscape, national forest, state, region, etc. The following section provides an overview of potential applications of *TRIAD*.

The discussion of potential applications of *TRIAD* requires mention of the accuracy of the parameters and the utility of coarse grain information. By necessity, terrain analysis at large scales (e.g., watersheds, landscapes, national forests, states, and regions) must utilize coarse grain information (e.g., Figure 1 and see discussion in 2.2). Coarse grain analysis includes the use of digital elevation data (presently 10-m), other open source databases, aerial photography, and rapid field recognizance. Consequently, terrain information tends to be more general than specific. For example, 10-m DEMs may not resolve all small-scale topographic features pertinent to landslide locations (i.e., such as individual bedrock hollows, see Figure 6 A, B). However, mapped erosion potential can resolve topographic controls over larger areas, such as the relative number of landslides to expect in two different first-order or larger basins (e.g., Figures 8 and 9). The same scale issue applies to channels. Although DEMs cannot resolve small, reach-scale morphological variations due to log jams, channel meanders, and bedrock outcrops, they can provide an overall spatial distribution of general channel types throughout a watershed based on 10-m analysis of gradient and confinement, etc. *TRIAD* parameters can be used for comparative analyses across dozens to hundreds of watersheds because coarse grain information allow analysis over tens of millions of acres rapidly and at low cost. *TRIAD* offers the ability to search, sort, rank, compare and classify numerous watershed attributes relevant to riverine ecology and natural resource management. Field validation is encouraged, particularly when terrain analysis is applied to site-specific resource management planning.

4.1 Integrating Parameters with Software Tools

The suite of parameters in *TRIAD* (e.g., Figures 4 – 48) can be utilized on their own for decision support in natural resource management. However, the applications to resource management (summarized below) can be made more efficient when they are performed in conjunction with web-based *software tools* (currently in development by ESI and to be presented in Part II of this manual). Software tools will allow easy access to large databases covering millions of acres (Figure 50), from which comparative analyses (i.e., sort and rank of various watershed attributes) can be made (Figure 51). ESI terrain software will allow for analyses to range from populations of watersheds to an individual watershed in support of project-level resource management (Figure 52**)**. For example, the parameter database in conjunction with the software can support resource management, restoration, and conservation at the scale of individual watersheds by utilizing map-based information (Figure 53). Decision support at the scale of landscape planning can utilize the queryable databases from which subbasins can be sorted, ranked, and classified according to relevant watershed attributes (Figure 54).

The software will also allow users to archive links to various other sources of formal (i.e., published) and informal information pertinent to particular watersheds (Figure 55). Photos and personal experiences can also be archived. This will encourage information dissemination and communication among diverse agencies and users. Refer to Part II of the manual due out in 2006 for further details.

All of the example applications for natural resource management briefly described below could be made in the context of the software tools currently in development.

Associated Software Tools

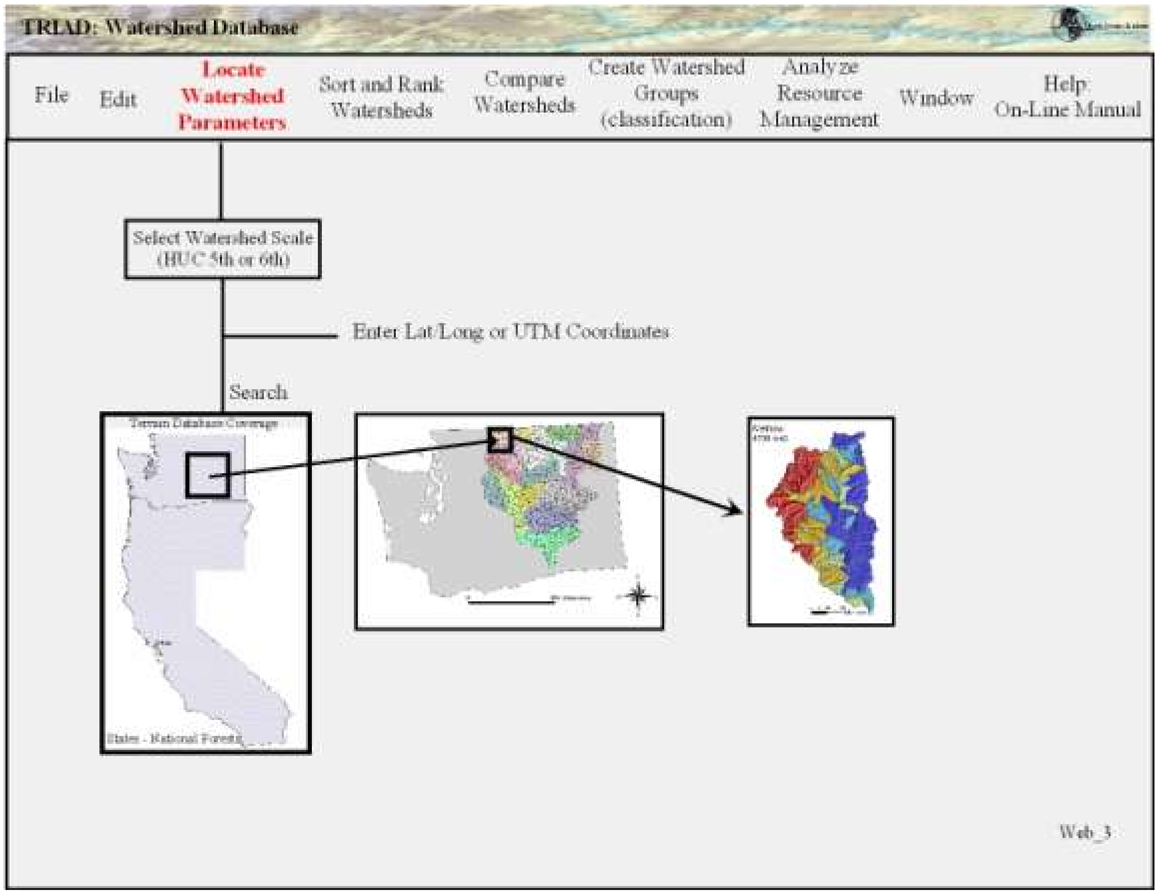


Figure 50. To efficiently use and manipulate the numerous parameters in the Terrain Resource and Inventory Database, Earth Systems Institute (ESI) is developing a suite of software tools. The main watershed window is shown here.

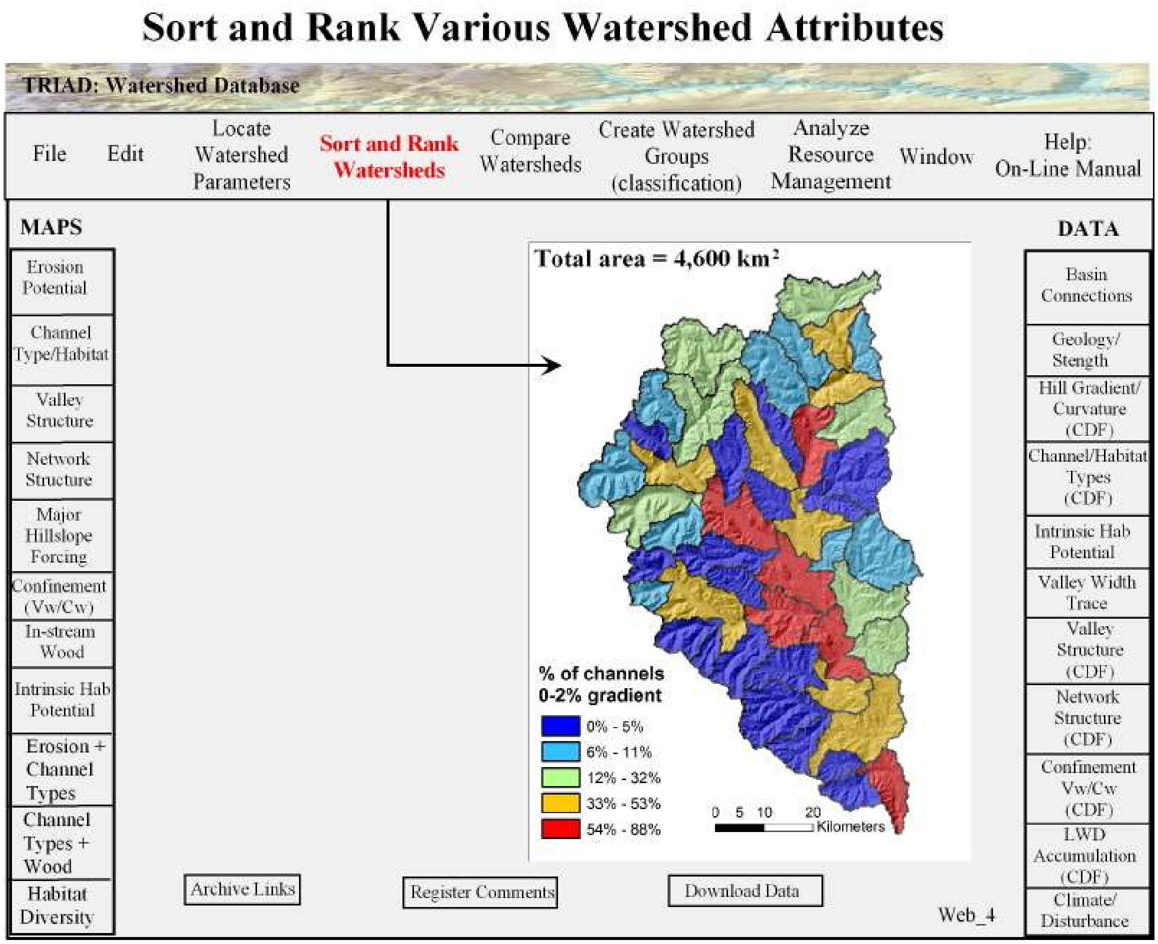


Figure 51. The database parameters used in conjunction with software tools offer theunprecedented ability to search, sort, rank, and classify various watershed attributes. Menus include map-based data (left side) and queryable data in the form of distribution functions and single value parameters (right side). A users manual supports the analyst's integration of the database with the software.

Population of Watershed to Individual Watersheds

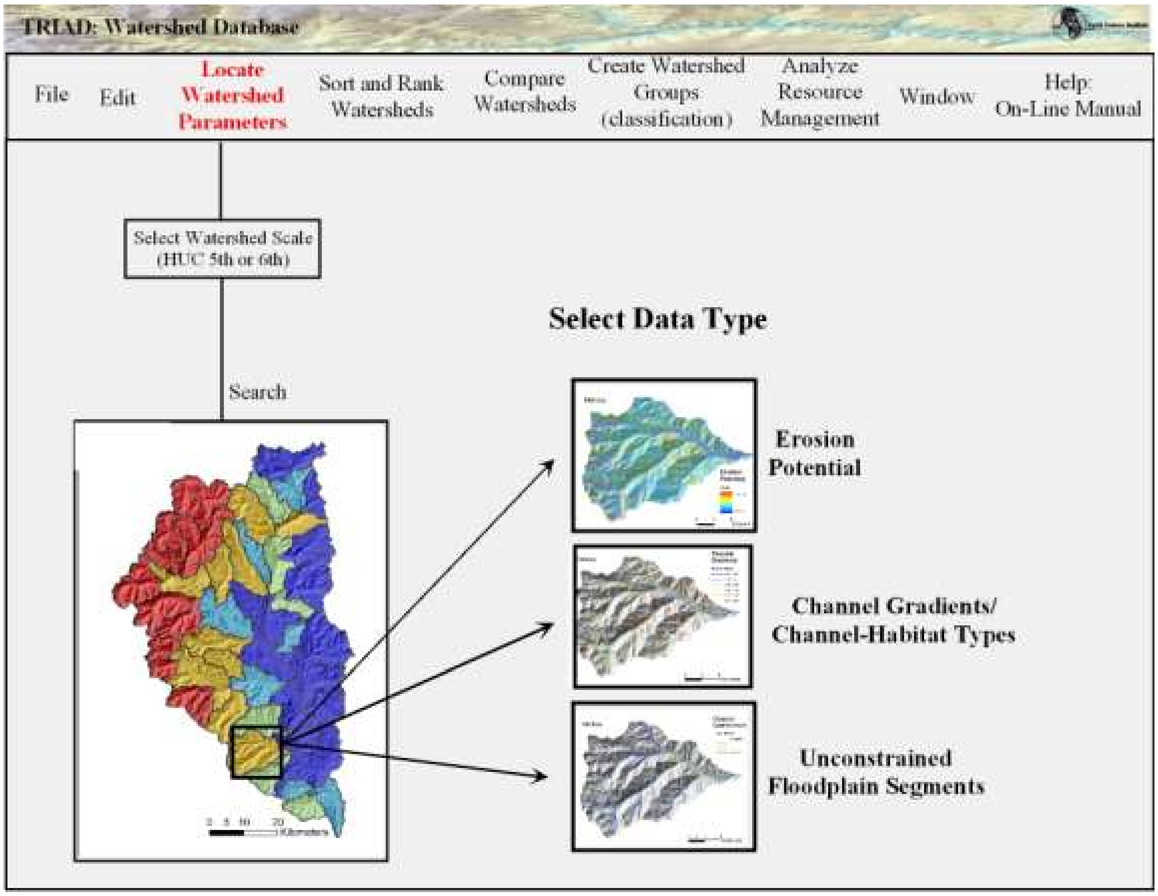


Figure 52. The database used in conjunction with the software will allow an analyst to quickly change the scale of investigation from populations of subbasins to individual smaller watersheds to examine such things as erosion potential, channel and habitat types, and valley segment types, etc. Hence one can quickly shift from landscape-level planning to individual watershed planning.

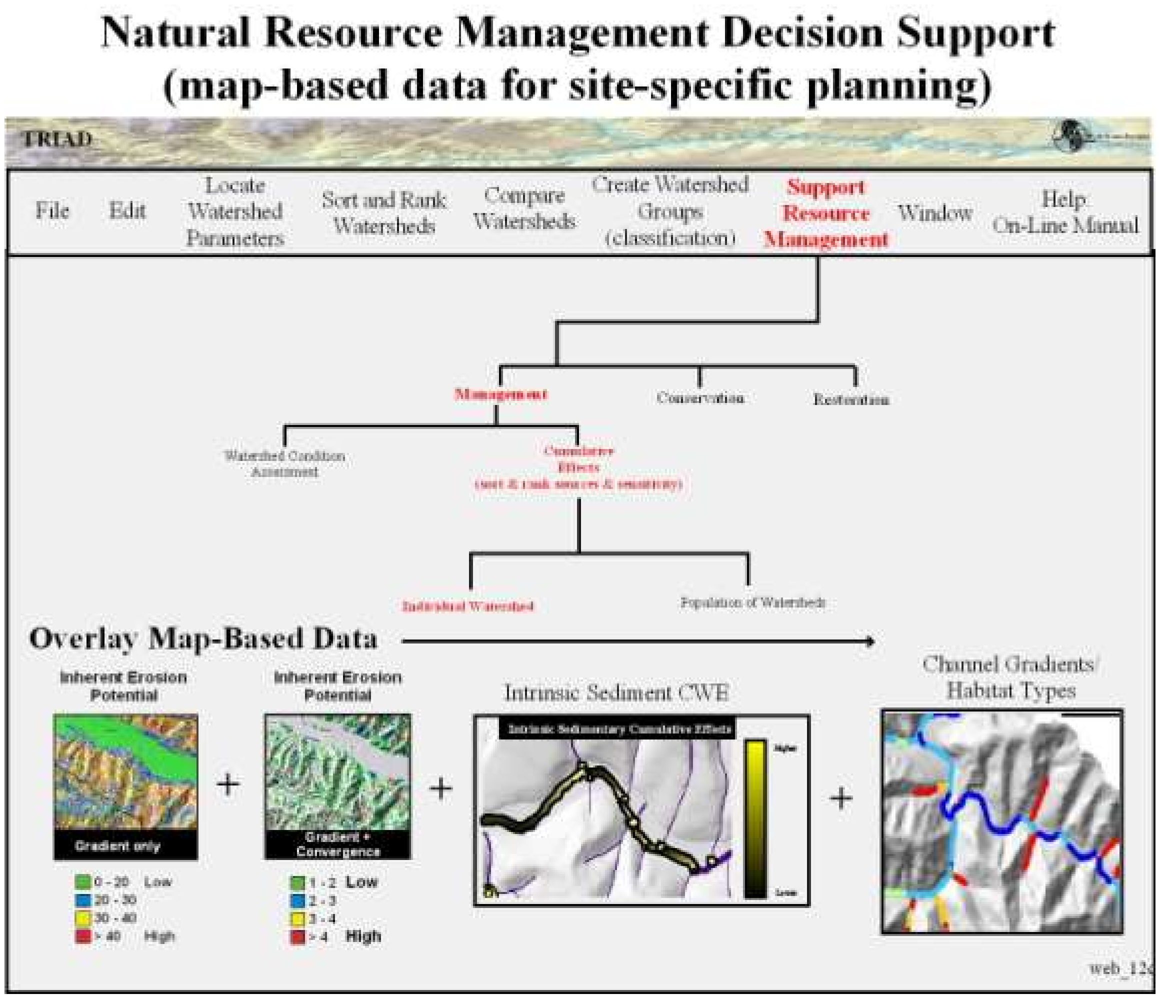
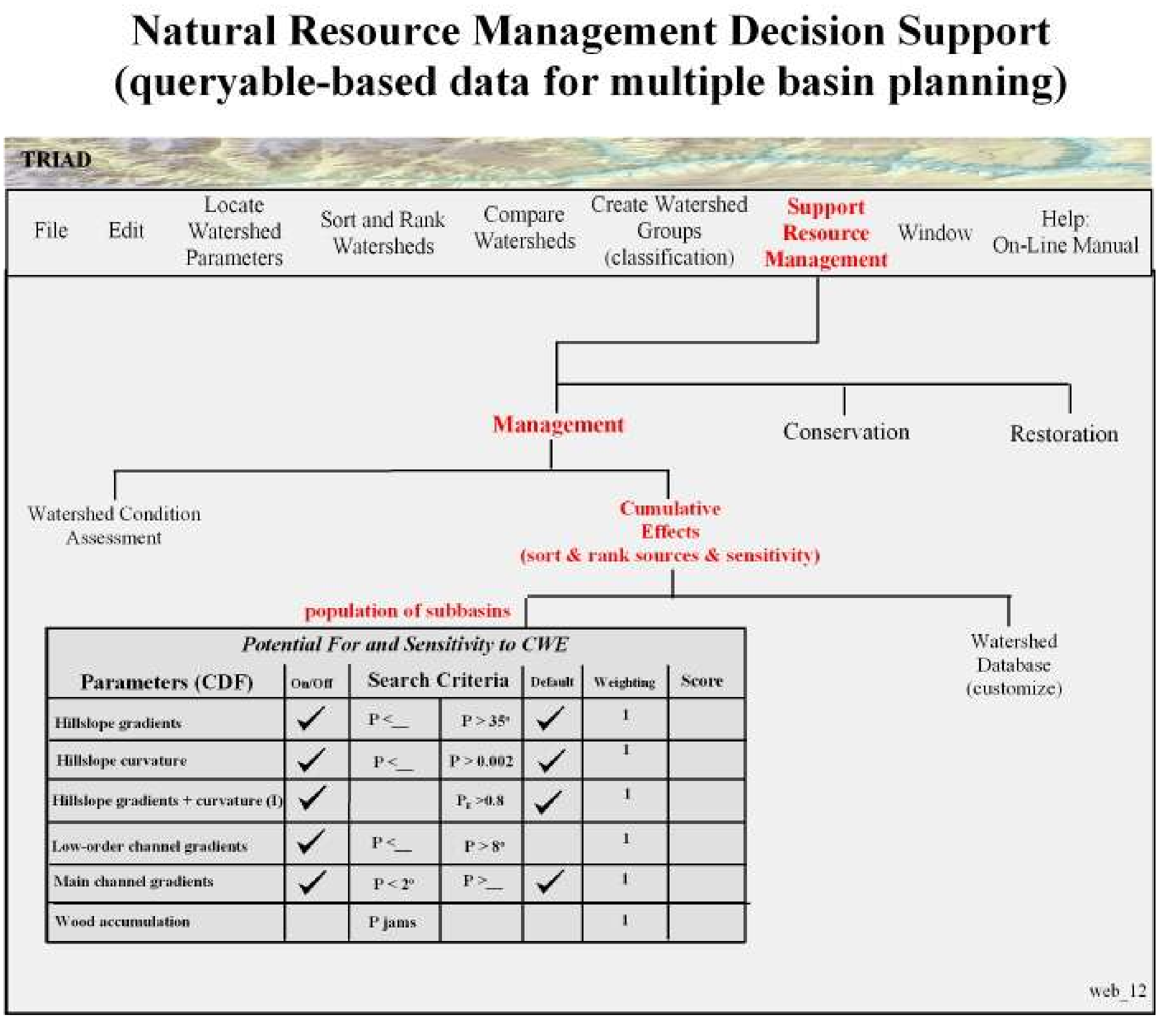


Figure 53. The software that utilizes the database can guide users through selection of appropriate map overlays for various natural resource applications. For example, an assessment of a channel's intrinsic exposure and sensitivity to increased sediment supply could employ the map-based data of: 1) inherent erosion potential, 2) intrinsic sediment exposure, and 3) channel gradients and types, among other parameters.



Parameters (CDF)	On/Off	Search Criteria		Default	Weighting	Score
Hillslope gradients	✓	P <__	P > 35°	✓	1	
Hillslope curvature	✓	P <__	P > 0.002	✓	1	
Hillslope gradients + curvature (I)	✓		P_I >0.8	✓	1	
Low-order channel gradients	✓	P <__	P > 8°		1	
Main channel gradients	✓	P < 2°	P >__	✓	1	
Wood accumulation		P jams			1	

Figure 54. The software and the database can guide users through selection of appropriate levels of queryable parameters for cross-basin comparison among a population of watersheds at the scale of large drainage basins, national forest, and regions. The default set of parameters can be turned on and off and search criteria (within cumulative distributions) can be set by the user and be given certain weightings.

Archive Links to Other Watershed Information

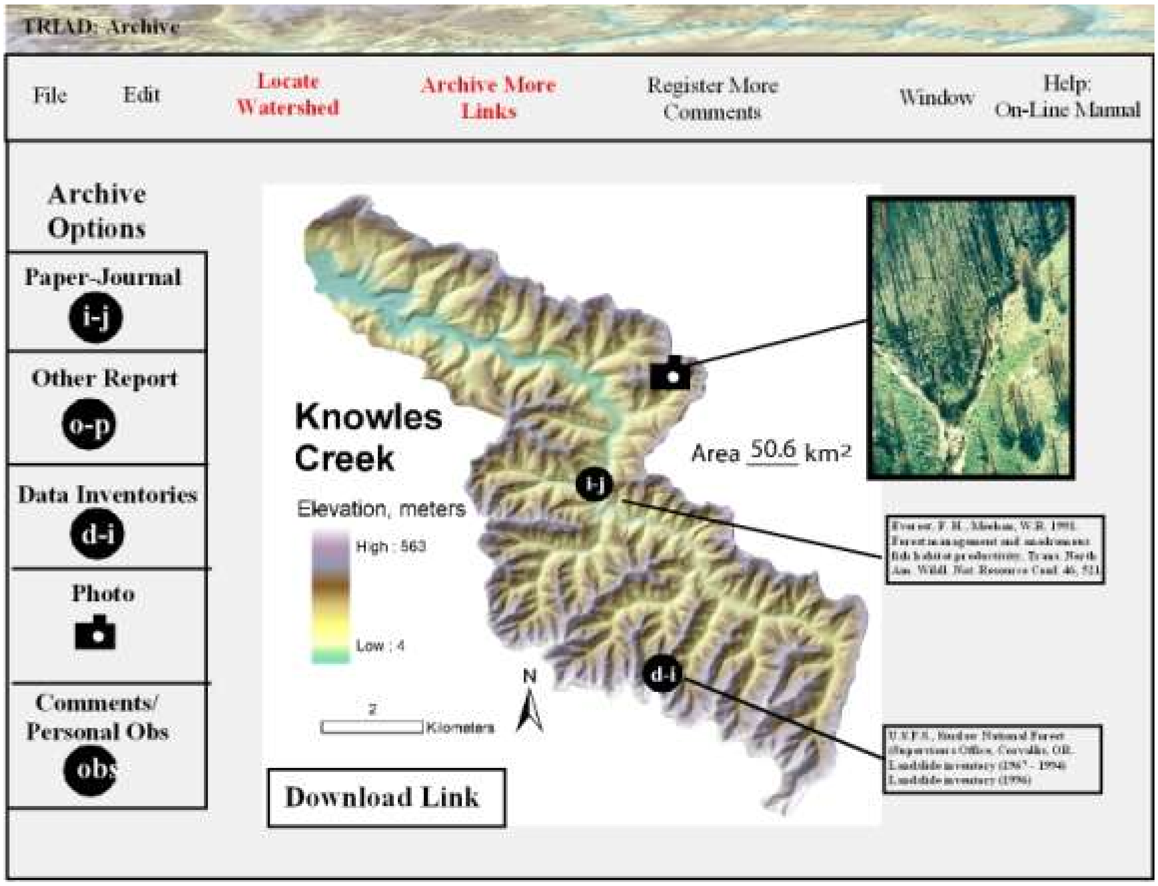


Figure 55. A common refrain among watershed scientists and planners is that their wealth of personal information and experiences about a landscape goes out the door when they leave their professional positions or retire. Not any longer. The *TRIAD* database in conjunction with the software tools will allow users (from any agency) to quickly archive links to other information and databases, including professional papers, other reports, data inventories, photos, and personal observations, and to geo-spatially reference them to specific locations in a landscape or watershed.

4.2 *TRIAD* Parameters: Individually or in Combination

Single parameters can provide important information for understanding watershed environments. For example, maps of hillslope erosion potential (e.g., Figures 6, 8, and 9) or the CDF of erosion potential (Figure 7) can provide insights into the inherent risks across individual watersheds. The CDF of channel gradients can provide information on the proportion of channel networks having high quality fish habitats within a single basin or across a population of basins. Variation in valley widths provides information on the degree of floodplain development in a watershed as well as providing an index of habitat heterogeneity

TRIAD parameters can also be used in a variety of combinations to address questions pertinent to riverine ecology and natural resource management within an individual watershed. For instance, information on hillslope erosion potential can be combined with information on riverine habitats to identify sensitive areas of watersheds. Information on the climate-based disturbance regime of a watershed can be integrated with the spatial structure of river networks (channel gradients, valley widths, and tributary confluences) to help understand the role of extreme events (i.e., natural disturbance) in shaping riverine habitats. Moreover, a suite of parameters can be combined to create various holistic indices of watersheds or landscapes. For instance, the complexity or diversity of riverine environments can be ranked from the most complex to the most simple (Figure 56). Complex watersheds would tend to have highly variable hillslope and channel gradients, highly variable valley morphology, high density of geomorphically-significant confluences, high drainage and confluence density, and prone to various types of disturbances. Fiordland-type landscapes in humid coastal mountain ranges might fit this category. In contrast, simple landscapes would tend to be gentle with little variability in valley widths and channel types, and a low drainage and confluence density. Watersheds located on arctic plains or steppes might fit this category. The complexity of landscapes may have ramifications for habitat diversity and possibly for biological diversity (Benda et al. 2004a).

The following sections briefly summarizes several potential applications of *TRIAD*, including: 1) identifying high erosion potential for stratifying land use (including fuels management), 2) identifying the best habitats, 3) predicting intrinsic habitat potential,

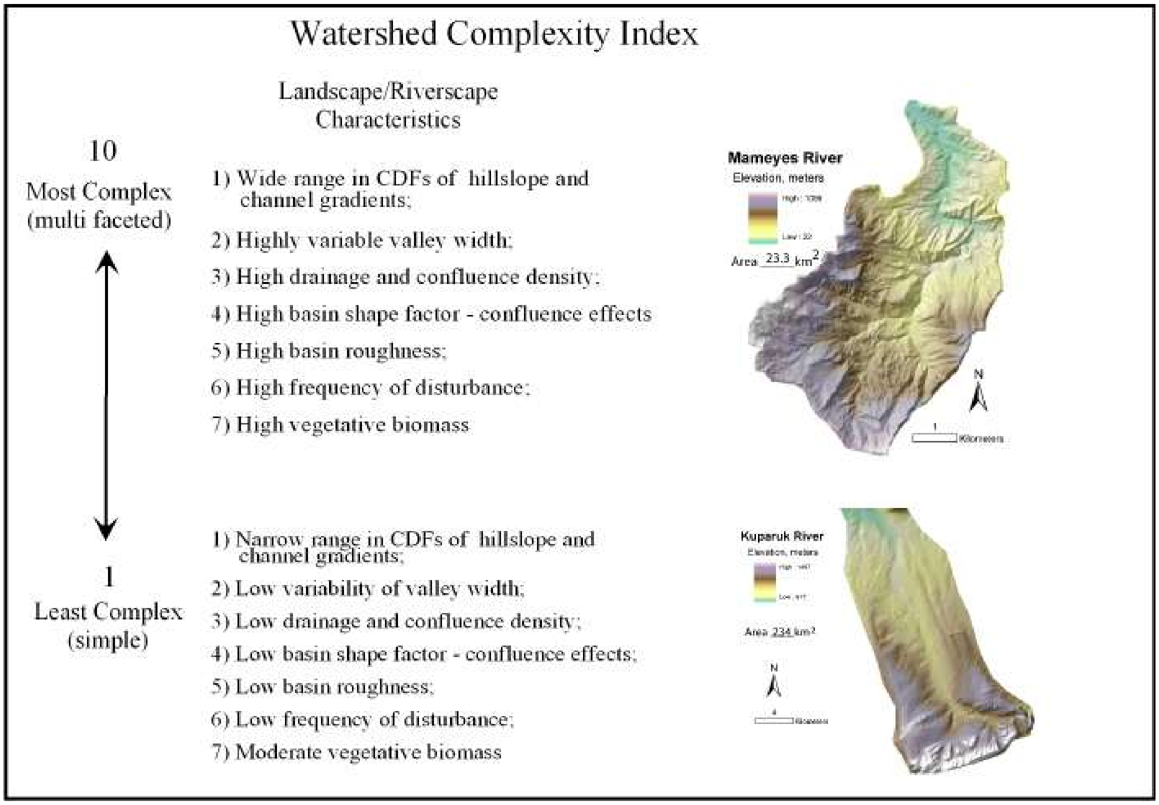


Figure 56. The database parameters allow for the creation of various holistic indices about intrinsic watershed conditions. Shown here is a suite of parameters that could be used to sort and rank watershed complexity that could have implications for riverine heterogeneity. For example, the Mameyes River basin in Puerto Rico might be considered a highly complex watershed compared to the Kuparuk River basin located on the arctic plain.

4) detecting potential biological hotspots, 5) locating high value conservation areas, 6) prioritizing habitat restoration areas, and 7) identifying habitat diversity. Refer to Part III of *TRIAD* Users Manual for more in depth discussion of applications (in progress).

4.2.1 Identifying High Erosion Potential: Individual Watersheds and Populations of Watersheds

Certain type of erosion processes can be viewed as a risk to aquatic resources, particularly over the short term. Areas in watersheds that are prone to mass wasting, for example, can be identified using TRIAD parameters (e.g., Figures 6 through 9). Sites with high landslide and debris flow potential could be excluded from high intensity resource use, such as timber harvesting and road construction. Similarly, areas of low risk could be targeted for higher intensity resource use (Figure 57).

Of particular relevance in the western U. S. over the last decade is the environmental concern regarding healthy forest initiatives including forest thinning operations and post-fire salvage logging of dead or dying trees. A point of concern is how such timber harvesting and associated road construction will increase erosion, including mass wasting and hence the ecological impact to channels. The intrinsic erosion potential (Figure 6, D) or the models predicting the relative likelihood of shallow failures and debris flows in particular landscapes (e.g., Figures 8 and 9) could be applied to identify suitable locations for certain silvicultural treatments (Figure 58).

Indices of erosion potential also could be overlaid with parameters covering aquatic habitat quality and sensitivity. For example, areas predicted to have high erosion potential that overlap with areas of high quality habitats might warrant higher degrees of protection while areas of low erosion potential or areas of higher erosion potential that do not overlap with high quality habitats could be targeted for less protection and more intense resource management (Figure 59).

Individual subbasins in very large watersheds can be sorted and ranked with respect to erosion potential. This type of analysis might be useful for planning at the scale of landscapes or national forests (Figure 60).

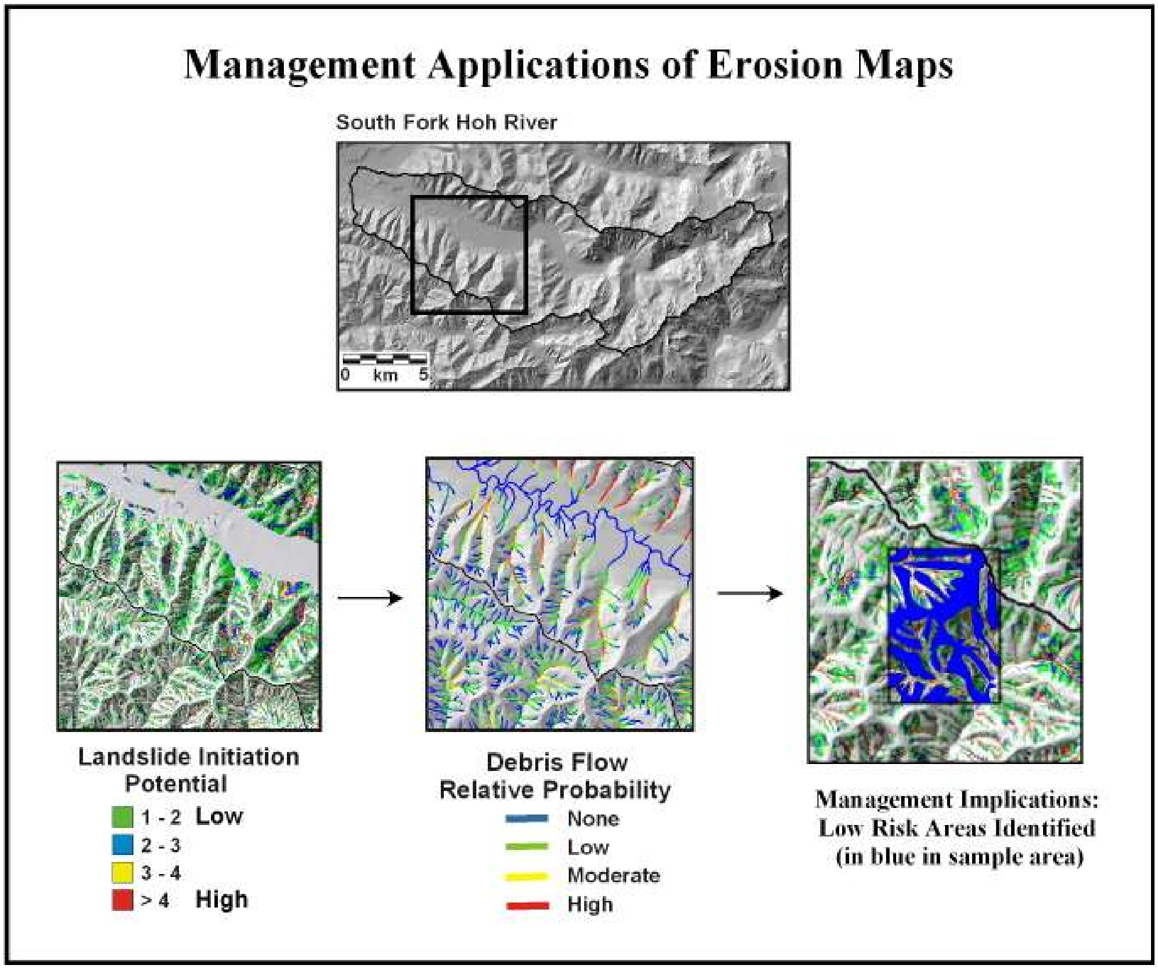


Figure 57. There are numerous potential applications of the database parameters. One of the most obvious is the use of inherent landslide and debris flow potential to identify low risk areas that might be suitable for more intensive resource use.

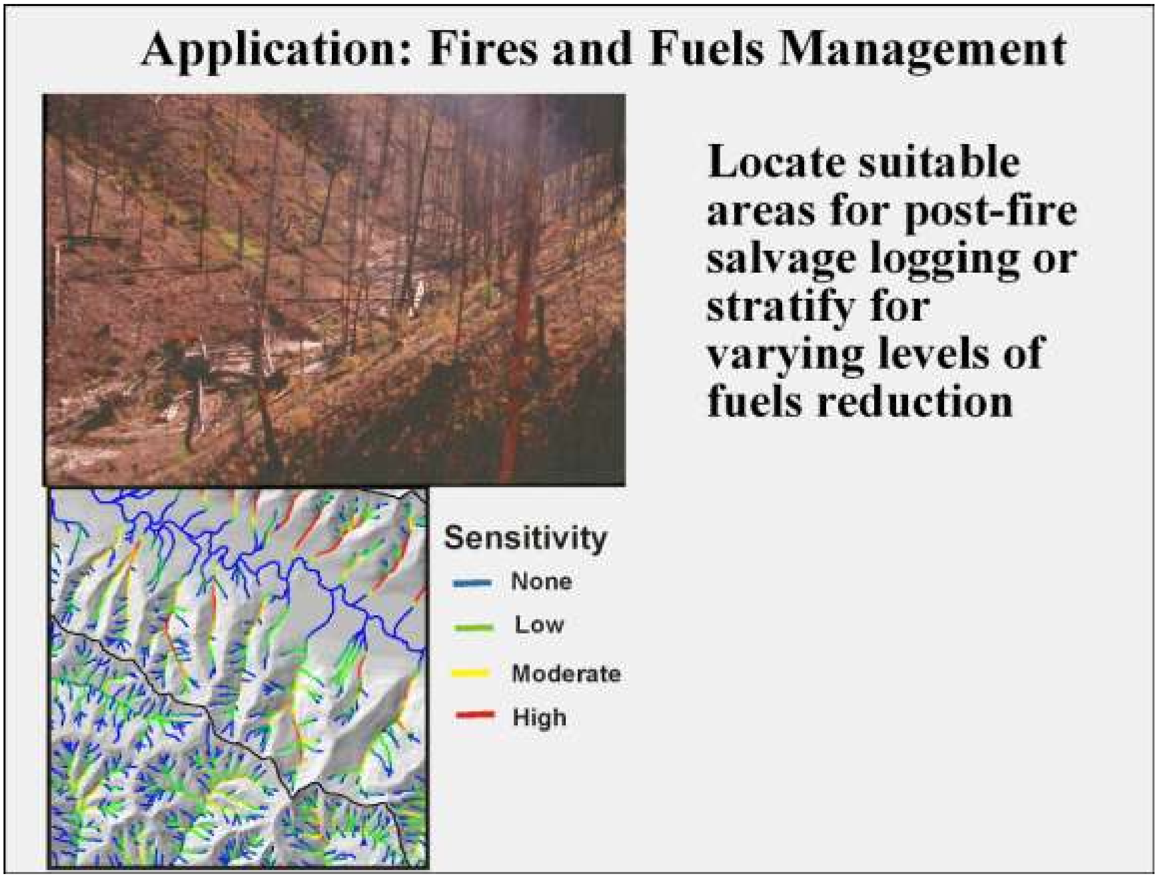


Figure 58. The use of erosion sensitivity predictions can be extended to areas where pre-fire thinning or post-fire salvage logging are a part of forest management plans. Areas of high sensitivity could be avoided (also to maintain sources of large wood to streams in the event of failures following fires). Maps and databases of erosion sensitivity could be combined with other related parameters such as a channel's intrinsic sediment exposure (e.g., Figure 43) and sensitivity to change (e.g., Figure 35).

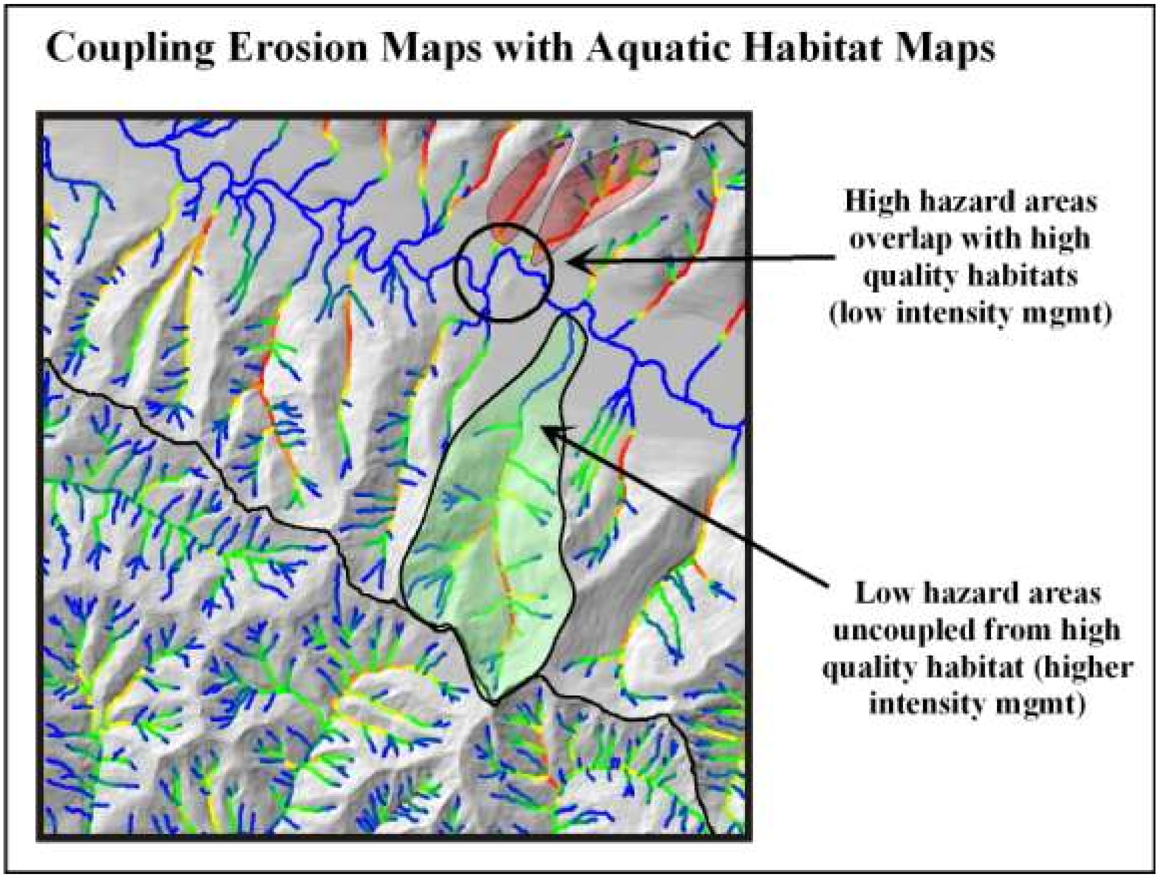


Figure 59. One important task in resource management planning is predicting likely impacts to aquatic resources. Information on erosion sensitivity can be overlaid with parameters that describe the quality and sensitivity of river habitats. Where high-risk erosion areas overlap with high quality habitats, low management intensity might be warranted. Higher intensity management could be planned for areas where no such environmental overlap occurs.

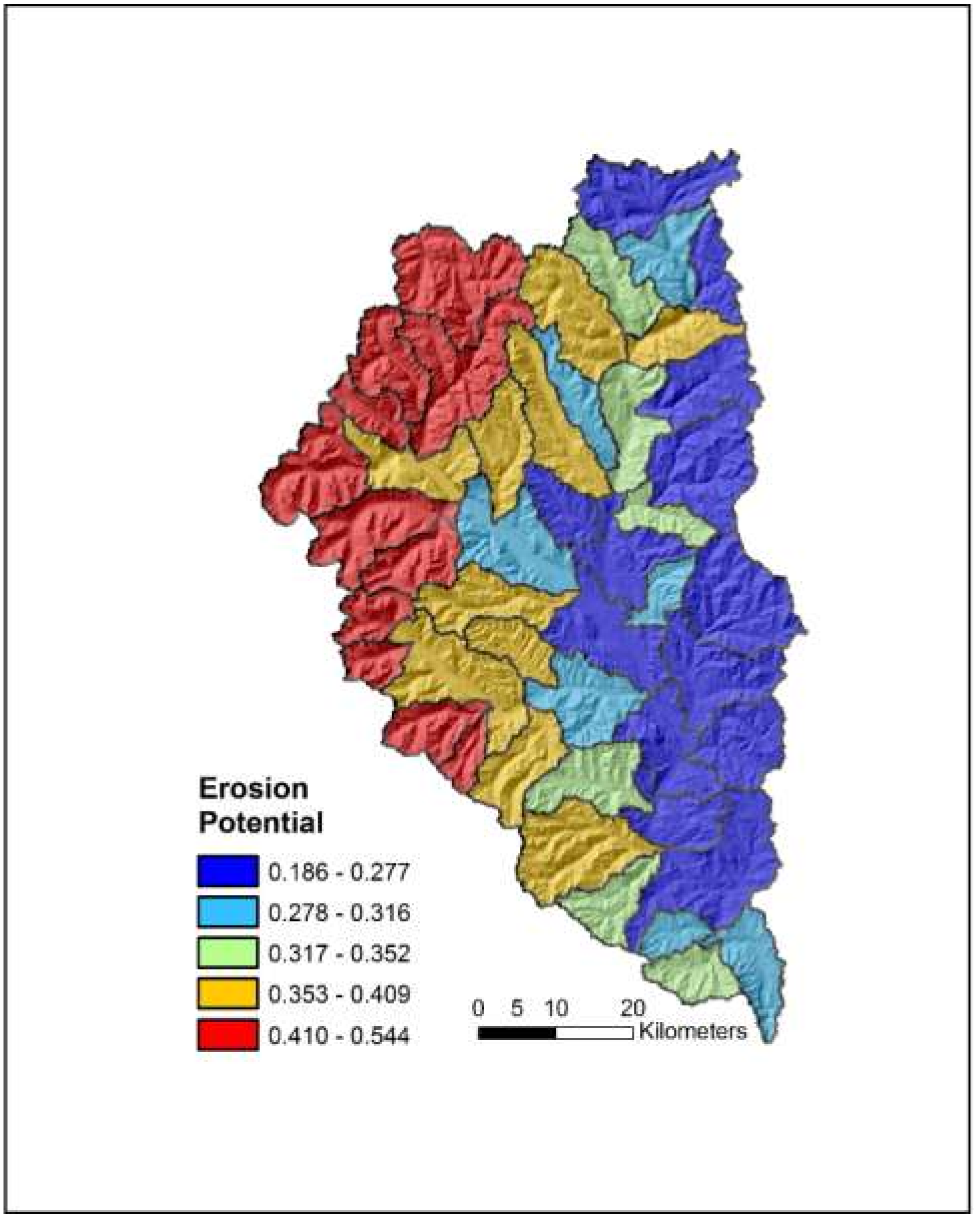


Figure 60. At the scale of large drainage basins, national forests, and regions, subbasins can be sorted and ranked according to intrinsic erosion potential. The ability to differentiate erosion potential at this scale is useful for landscape-level or forest-level planning by a host of federal and state agencies. Screening at this scale can then lead to management planning at individual subbasins using map-based data (e.g., Figure 52).

4.2.2 Identifying the Best Habitats: Individual Watersheds and Populations of Watersheds

River habitats have many defining characteristics, depending on species diversity and life histories. Characteristics of high quality habitats may include channel gradient, valley confinement, proximity to confluences, and wood accumulations etc. TRIAD parameters can be used to map out the intrinsically best habitats based simply on gradient and confinement at the scale of individual watersheds or populations of watersheds (Figure 61). Watershed parameters, such as CDFs of gradient and valley confinement, can also be used to compare habitat types and quality across two or more watersheds (Figure 62). Comparisons of habitat types can be made across dozens of watersheds for large scale planning or screening purposes (Figure 63).

4.2.3 Predicting Intrinsic Habitat Potential

TRIAD parameters could be used to support other indicators of fish habitat suitability. For example, Burnett et al. (2003) related habitat quality of coho salmon (Oncorhynchus kisutch) and steelhead trout (Oncorhynchus mykiss) to measures of channel gradient, valley confinement, and mean annual discharge in coastal Oregon. In general, coho salmon prefer lower gradient and wider channels compared to steelhead that are often found in abundance in steeper reaches (4 – 6%) and in more confined valleys. Predicted intrinsic habitat potential could be displayed on maps and CDFs could be created for comparisons among populations of basins (Figure 64). See also http://www.fsl.orst.edu/clams.

4.2.4 Detecting Potential Biological Hotspots

One implication of the characteristically non-uniform distribution of river habitats (e.g., Figure 2) is that high value habitats might be isolated to particular areas within a watershed. Juxtapositions of certain riverine environmental conditions such as gradients, valley confinement, tributary confluences, stream-adjacent topographic roughness, mass wasting features, and wood accumulations, etc. have the potential for creating diverse and productive habitats. This type of information in TRIAD can be displayed on maps or queried from

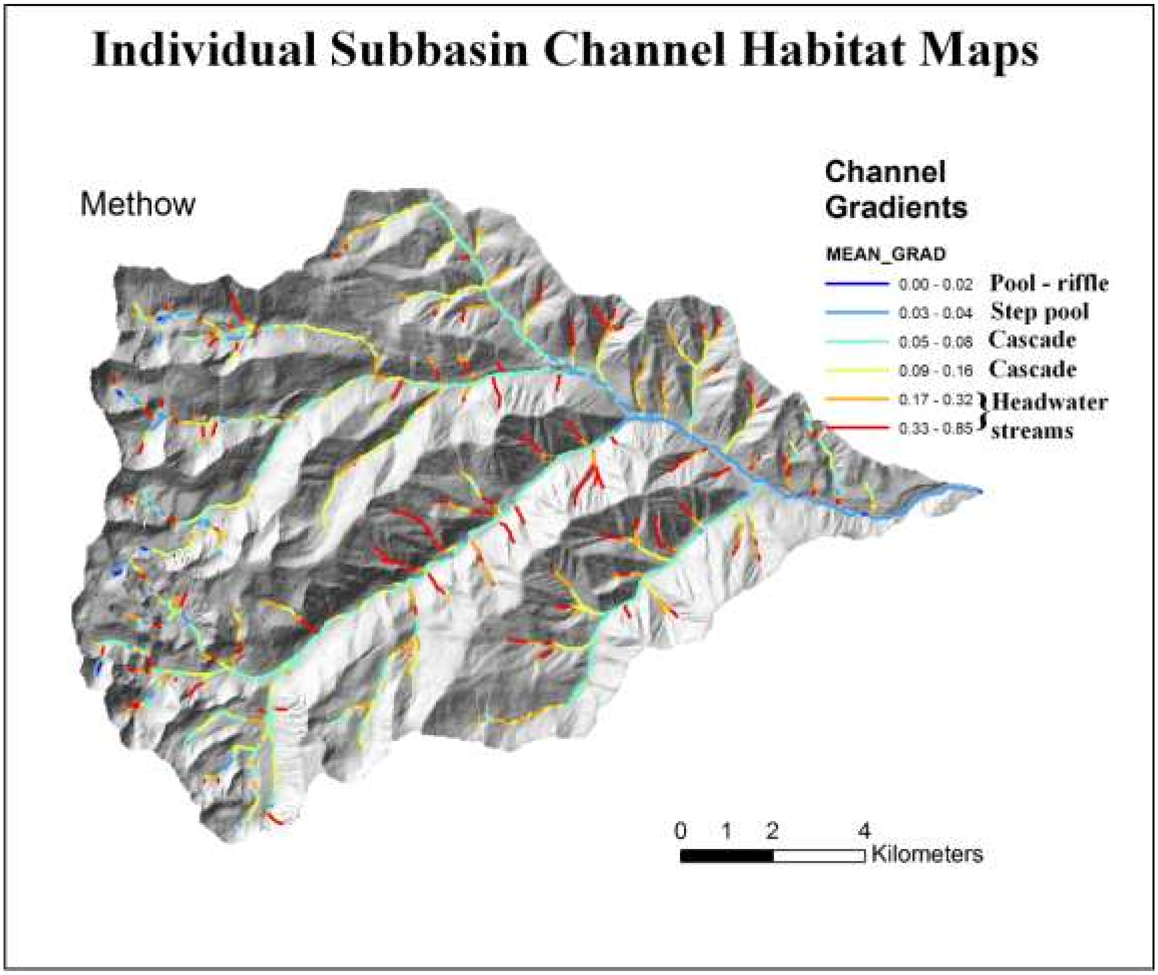


Figure 61. An important indicator of quality aquatic habitat is channel gradient that often is an accurate proxy for habitat type. The locations of the best habitats can be quickly screened at the subbasin scale and overlaid with other parameters including wood accumulations, stream-adjacent topographic roughness, valley morphology, and geomorphically-significant confluences.

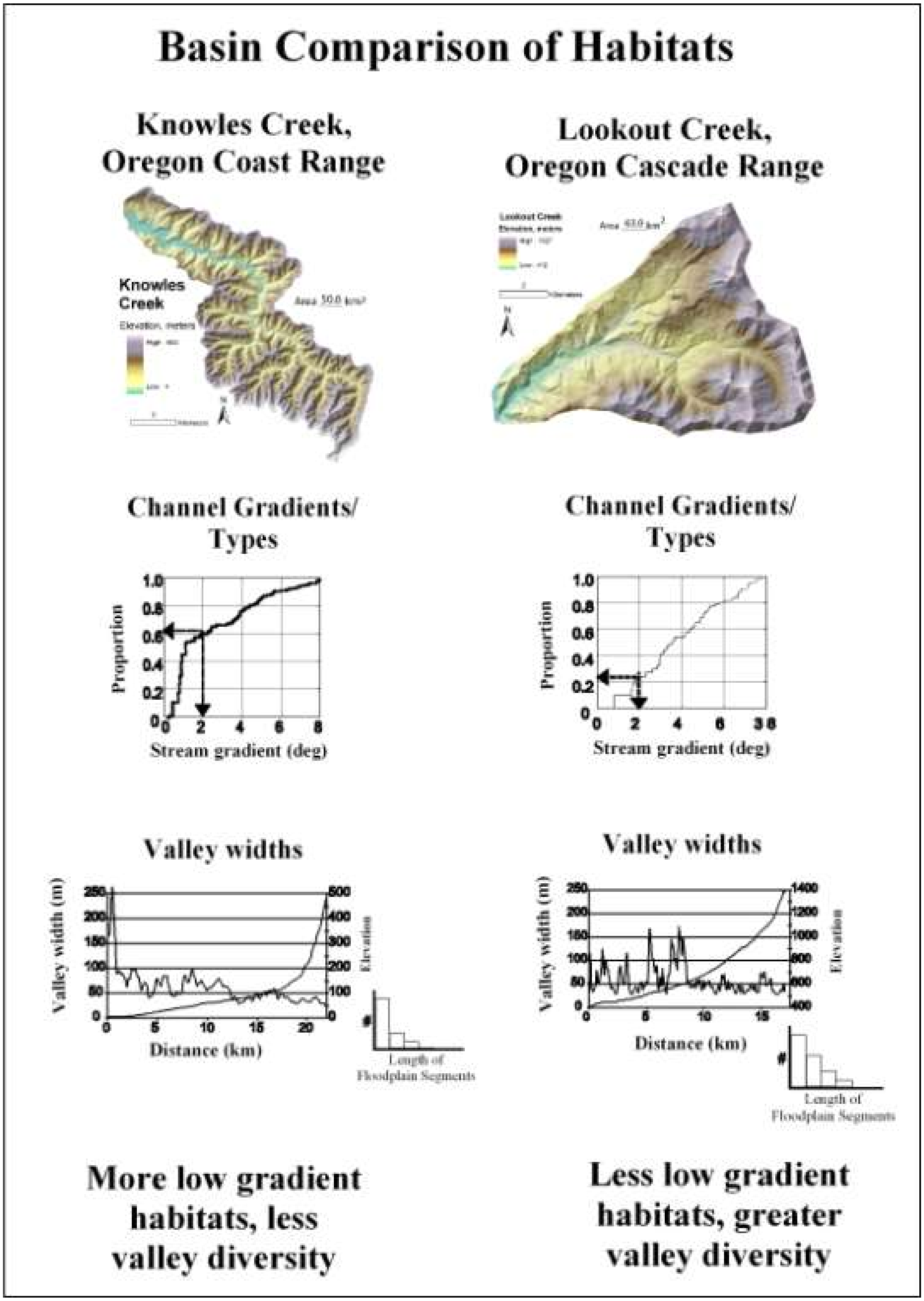


Figure 62. Cross basin comparisons can be conducted using cumulative distribution functions (for example slope gradient) and longitudinal plots of valley widths to identify key differences in environmental conditions that could be used to tailor resource management, restoration, conservation, and monitoring activities.

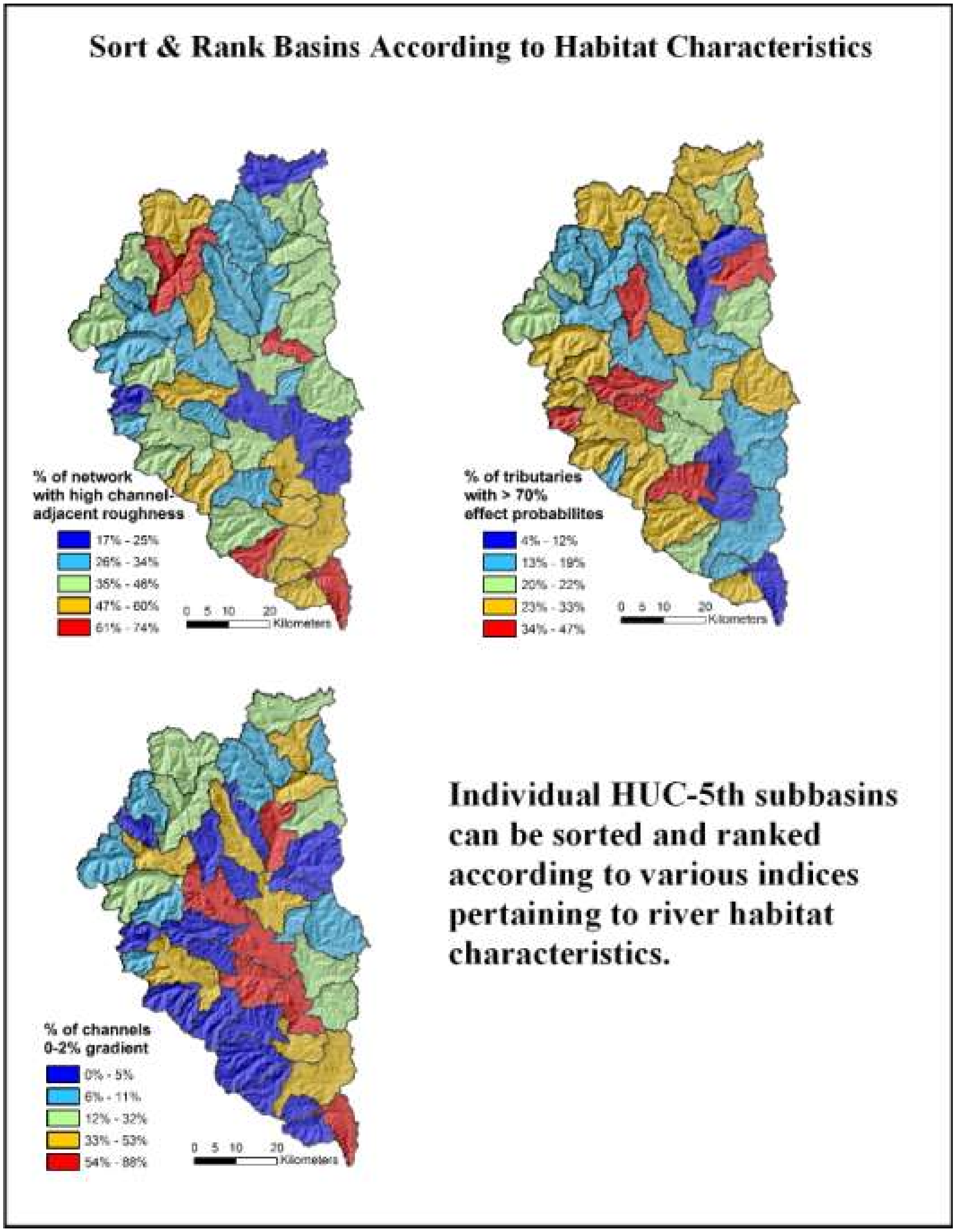


Figure 63. A suite of parameters can be used to sort and rank various attributes of riverine habitats. The conjunction of habitat indicators such as channel gradient, roughness, and confluences can be used to identify individual watersheds with the highest intrinsic habitat potential and/or heterogeneity.

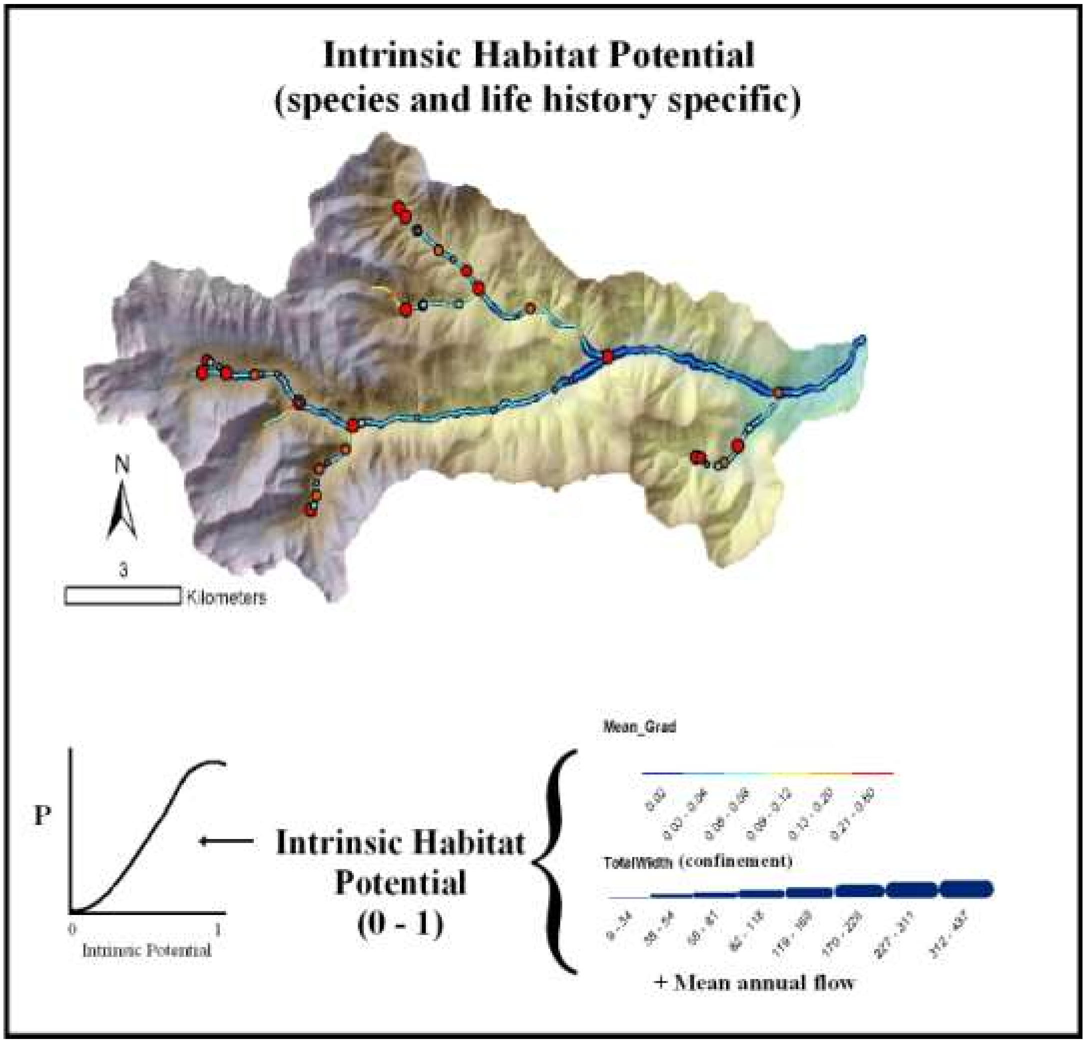


Figure 64. Simple measures of intrinsic habitat potential, such as channel gradient, confinement, and mean annual flow can be used as a screen from which to evaluate habitat potential at scales of individual watersheds to landscapes (Burnett et al. 2003).

CDFs of those parameters (Figure 65) and can be used by the land manager to identify high-value habitats for protection, restoration, and monitoring.

4.2.5 Locating High Value Conservation Areas

Information about basin shape, network configuration, significant geomorphic confluences, and valley segment morphology has applications for resource conservation (as well as restoration). Maps showing locations of geomorphically significant confluences and variations in valley widths could be used to identify zones meriting extra protection or conservation (Figure 66). Locations of geomorphically significant confluences that overlap with wide valley segments may identify ecologically interesting and productive aquatic and riparian habitats. Other interesting combinations of the various parameters that might be useful in identifying high value riverine habitats is left to the user's professional training and imagination. See Part III of TRIAD Users Manual for more in depth discussion of applications.

4.2.6 Prioritizing Areas Suitable for Habitat Restoration Projects

The success of in-stream restoration projects to enhance aquatic habitats depends on a variety of factors. On one hand, success might be gauged by whether the best intrinsic habitat environments are targeted for restoration within a single watershed or across a population of sub-watersheds within a larger drainage basin. This would require knowledge of the different types and distributions of various habitat conditions at several different scales. For example, in-stream log structures should be placed in channels that historically had wood jams and where channels are not excessively dynamic.. TRIAD parameters could be used to locate such environments. In addition, identifying variation in intrinsic habitat across basins (e.g., Figure 64) or identifying potential biological hotspots (e.g., Figure 65) could also provide a context from which to prioritize restoration projects.

Another issue in restoration concerns the stability of the channel being restored. Channels that are highly dynamic may be least suitable for certain types of restoration projects and those channel types might also lend themselves more to restoration by natural processes, including floods and certain forms of erosion. Potentially unstable locations for restoration may include sites immediately upstream and downstream of canyons, confluences of certain

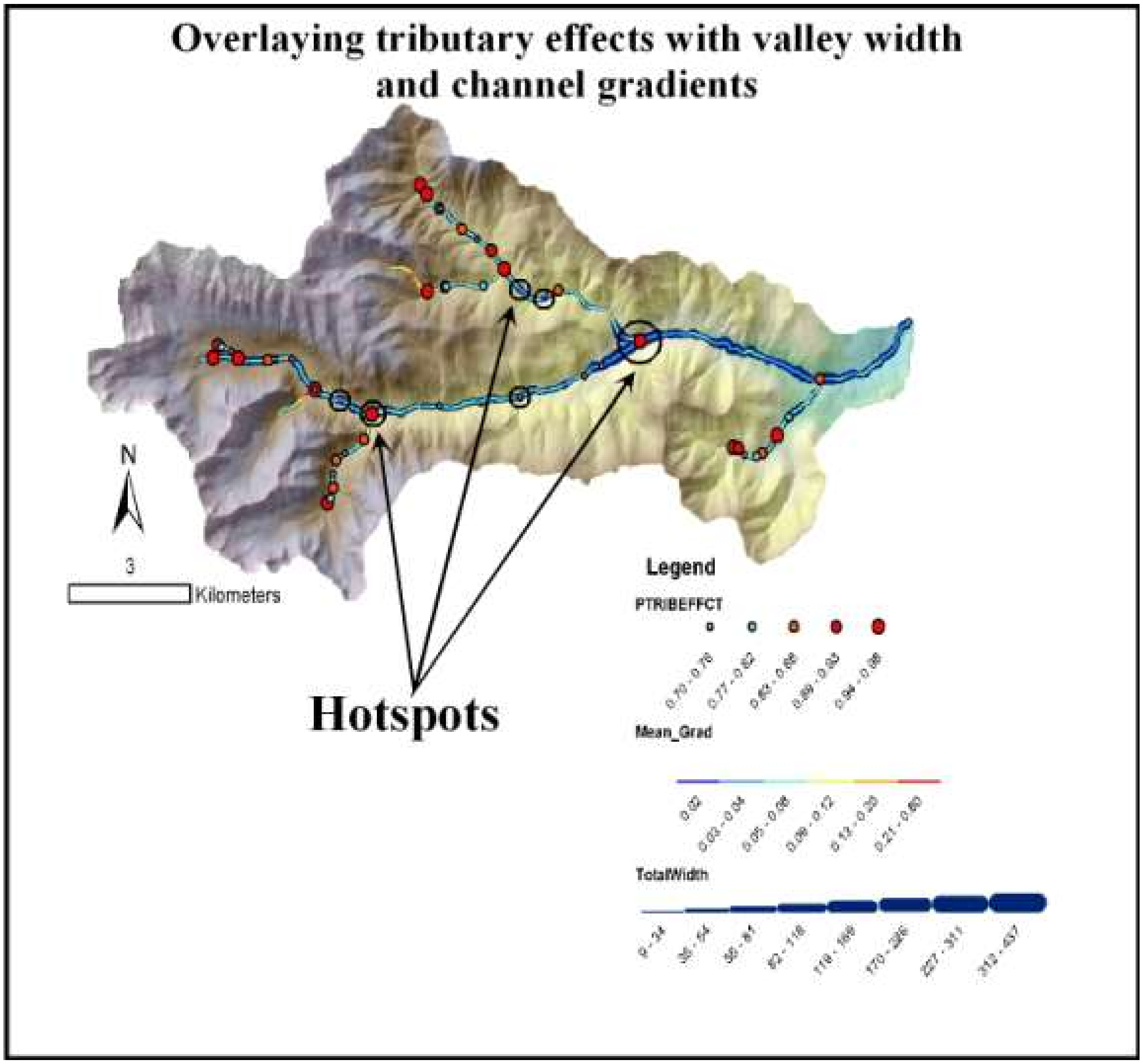


Figure 65. The characteristically non-uniform distribution of habitats (e.g., Figure 2) in watersheds indicates that the best habitats (i.e., "hotspots) will be isolated to certain areas. The overlap of certain habitat indicators could be used to identify such zones for increased protection, restoration, or monitoring.

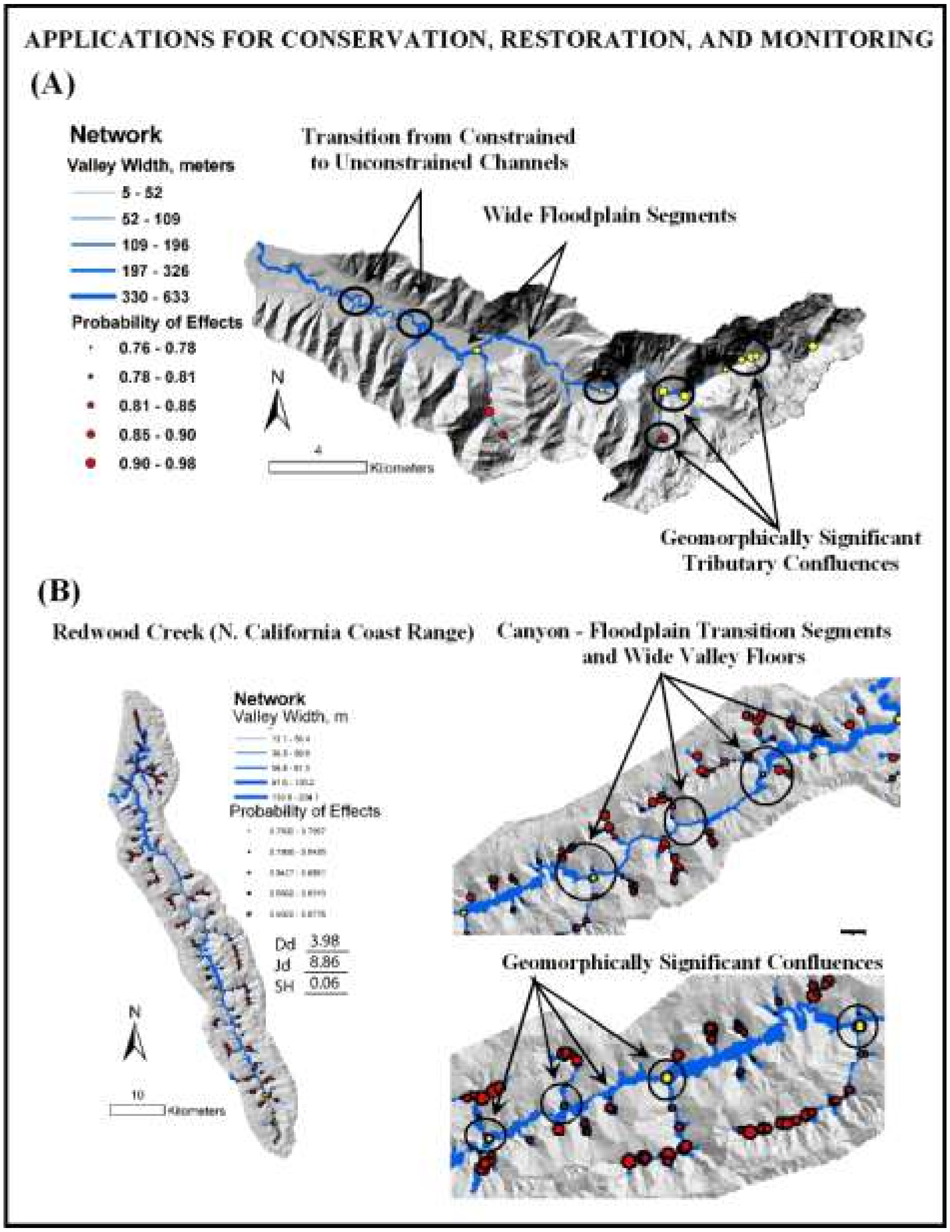


Figure 66. Identifying the non-uniform distribution of potentially high quality habitats can be used to prioritize conservation, restoration, and monitoring.

tributaries (both up- and downstream), and toes of large landslides. These areas could be avoided during restoration planning and *TRIAD* parameters could be used to help identify them (e.g., Figure 66).

5. CONCLUSIONS

TRIAD is comprised of a set of parameters focusing on the relationship between watersheds and their river systems that can be used for various applications by the natural resource management, regulatory, and conservation community. *TRIAD* is consistent with current themes in geomorphology and riverine ecology and utilizes numerical techniques for analysis of digital data. It incorporates parameters that look at not only average features and trends within a watershed, but also at deviations from those trends. The methods utilize computer-driven numerical calculations to perform analyses at the highest resolution (dependent on available data), and then integrate information to provide measures that characterize watershed properties over larger scales. This approach provides detail about both the suite and abundance of habitat types and about the degree and sources of habitat heterogeneity. This allows for comparative analysis of watersheds in terms of habitat potential and sensitivity to change. Because these measures can be defined over any spatial scale, *TRIAD* can provide information for different types of analyses, from timber-harvest planning and road layout to delineation of watersheds containing specific types or sensitive habitats. Such information should encourage increased communication and commonality of objectives among watershed stakeholders that may aid in decision making. This multi-scale capacity also allows examination of how watershed properties change when defined over different scales. We expect that use of such measures will enhance the usefulness of existing data sets for ecological assessments, leading to development of new hypotheses and understanding of landscape – riverscape linkages, and of human interactions within these systems.

In this Part I of the *TRIAD* Users Manual, we presented the conceptual and methodological foundations for the terrain analysis approach and an overview of the watershed database parameters. Part II will describe web-based software designed to efficiently use and manipulate the watershed terrain database, including the unprecedented ability to search, sort, compare, rank, and classify watershed attributes (in progress). Part III of the users manual will contain illustrative applications including examples of how to combine groups of database parameters to understand the geomorphic and ecologic attributes of watersheds for natural resource management (in progress). Also see www.earthsystems.net for additional information on the watershed terrain database, including the three components of the Users Manual as they become available.

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